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Positional comparison of isometric mid-thigh pull characteristics in youth female netball players

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ABSTRACT

To examine isometric mid-thigh pull (IMTP) characteristics of female youth netball players by position (defenders, centers and shooters). Data were collected on 50 regional youth players and comprised of height and body mass, and IMTP relative force-time characteristics (peak force [PF] and force at 50 [F_{50}], 100 [F_{100}], 150 [F_{150}], 200 [F_{200}] and 250 [F_{250}] milliseconds). These were compared across netball positions via a series of one-way analyses of variance. Centers demonstrated greater F_{50} ($p = 0.025$, [Hedges g] $g = 1.04$), F_{100} ($p = 0.020$, $g = 1.14$), F_{150} ($p = 0.048$, $g = 0.76$) and F_{250} ($p = 0.035$, $g = 0.84$) compared to defenders. No statistical differences ($p > 0.05$) were observed in any IMTP characteristic between defenders and shooters, yet effect sizes revealed practical differences ($g = 0.07$ to 0.85). Similarly, no statistical differences ($p > 0.05$) were observed in any IMTP characteristic between centers and shooters, yet effect sizes revealed practical differences ($g = –0.63$ to 1.21). These findings demonstrate that IMTP force-time characteristics differ between defenders and centers in youth female netball players. Practitioners should consider developing their netball players' peak and rapid force production capabilities, while considering the specific demands on individual positions.

1. Introduction

Success in netball is highly dependent on physical fitness characteristics including strength, power, speed, and agility (Young et al., 2016). To perform consistently throughout the 60-minute game and recover effectively between bouts of high-intensity exercise, netball players must also display a high level of aerobic fitness (Chandler et al., 2014). This has been highlighted in previous work (Chandler et al., 2014), with heart rates reported between 75-85% of the maximum heart rate during match play. Furthermore, match-play analysis reveals center-court players (center, wing attack, wing defense) cover more distance (Davidson & Trewartha, 2008) and accumulate greater Player Load (Cormack et al., 2014; Graham et al., 2020; Young et al., 2016), compared to defenders (goal keeper, goal defense) and shooters (goal attack, goal shooter). These differences are likely due to the differing roles of the positions combined with positional restrictions during play relating to which areas of the court individual players can play in.

Netball players must successfully complete multiple high-intensity short-duration sprints, cutting and pivot maneuvers, and up to 60 jump landings per game (Fox et al., 2012; Fox et al., 2014), all requiring high levels of concentric and eccentric force production to generate high braking and propulsive impulses in as short a time as possible (Mothersole et al., 2013). The literature provides normative data for sprint time (Graham et al., 2019; Thomas et al., 2016; Thomas et al., 2016), change of direction (Barber et al., 2015; Graham et al., 2019; Thomas et al., 2016; Thomas et al., 2016), vertical jump (Graham et al., 2019; Thomas et al., 2016), maximum strength (Thomas et al., 2016), and a range of other characteristics including anthropometric and aerobic capacity measurements (Graham et al., 2019; Thomas et al., 2016). However, very little is known about the maximal isometric force production capabilities (peak and time-specific force) across netball playing positions. Knowledge of maximal isometric force production capabilities of netball players by position would assist coaches and practitioners to prescribe appropriate training programs in line with the position-specific demands shown to exist during training and competition.

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Previously, researchers have shown youth female netball players to demonstrate isometric mid-thigh pull (IMTP) relative peak force values of 26.6 to 30.70 N·kg^{-1} (Dos'Santos et al., 2015; Thomas et al., 2016, 2017). Additionally, the study reported absolute and time-specific IMTP force values to differ between under 15 and under 19 age categories. Specifically, under 19 players produced greater absolute time-specific force values compared to under 15 and under 17 players. Furthermore, small differences in relative peak force and relative time-specific force values were found between age categories, with the exception of relative force at 200 ms, whereby under 19 players demonstrated greater values than both under 15 and under 17 players. Measures of peak force during the IMTP are closely related to performance in dynamic tasks such as sprint speed (Brady et al., 2019), change of direction speed (Brady et al., 2018), and vertical jump performance (Thomas et al., 2016). Furthermore, force at specific time points assessed during the IMTP has been related to sprint (West et al., 2011), jump (West et al., 2011), and dynamic strength measures such as maximal back squat strength (Wang et al., 2016). These findings clearly highlight the importance of maximum strength in female netball athletes. The importance of strength may be explained by the fact that peak ground reaction forces and more importantly, impulse are direct determinants of sprint (Weyand et al., 2000; Weyand et al., 2010), change of direction (Dos'Santos et al., 2019), and vertical jump performance (Kirby et al., 2011). Furthermore, greater levels of maximum strength may improve an athlete's ability to hold static, and achieve dynamic positions such as jumping and landing (Mothersole et al., 2013), sprinting (McBride et al., 2009) and change of direction (Spiteri et al., 2014), providing a greater acceleration, production of higher eccentric forces, thus preparing athletes for the movement demands and injury risks associated with the sport of netball. Additionally, peak force and time-specific force measures derived using the IMTP are shown to be highly reliable (Brady et al., 2018; Comfort et al., 2019; Guppy et al., 2019; Stone et al., 2019). The IMTP also has an acceptably low smallest worthwhile change, making it useful for tracking acute and chronic fatigue, and long-term training adaptations (Brady et al., 2018; Stone et al., 2019).

Most of the existing literature focuses on the physical demands of netball match-play (Chandler et al., 2014; Cormack et al., 2014; Davidson & Trewartha, 2008) and physical characteristics such as sprinting, change of direction and jumping (Graham et al., 2019; Thomas et al., 2016; Thomas et al., 2019). There are currently no normative data available in the published literature regarding position-specific IMTP force-time characteristics in youth female netball players. Additionally, this data can be used for talent identification and creating position-specific benchmarks for maximal isometric strength measures. Therefore, the aim of this study was to determine differences in isometric force-time measures between positions (centers, defenders and shooters) of youth female netball players. Based on previous research on physical characteristics (Graham et al., 2019; Thomas et al., 2019), it was hypothesized that center players would demonstrate superior isometric mid-thigh pull force-time characteristics, as compared with defenders and shooters. It was further hypothesized that defenders and shooters would demonstrate similar maximal and rapid isometric force production characteristics, based on previous work in physical profiling of netball players (Graham et al., 2019; Thomas et al., 2019).

2. Methods

2.1. Participants

Female youth netball players (n = 50; age = 15.57 ± 1.19 years; height = 1.71 ± 0.07 m; mass = 64.35 ± 7.67 kg; maturity offset = 3.00 ± 0.77 years) participated in this study. A priori statistical power calculations, using G*Power (version 3.1.9.7) indicated that for a statistical power of ≥0.90, and effect size of 0.60 at an alpha level of $p \leq 0.05$, a sample size of ≥39 was required. Subjects were all experienced (>2-years, 2–3 x/week) with all elements of resistance training, and all sessions were supervised by qualified (Certified Strength and Conditioning Coach [CSCS] with the National Strength and Conditioning Association and Accredited Strength and Conditioning Coach [ASCC] with the United Kingdom Strength and Conditioning association) strength and conditioning coaches. All subjects were free of injury at the time of testing. All subjects were fully informed of the requirements of the investigation and provided appropriate consent to participate, with consent from the parent or guardian of all players under the age of 18. The investigation was also approved by the institutional review board, in line with the Declaration of Helsinki.

2.2. Procedure

A cross-sectional observational design of a regional female netball youth academy in the United Kingdom was conducted whereby subjects were assessed on height and body mass, and IMTP force-time measures (peak force [PF] and force at 50 [F50], 100 [F100], 150 [F150], 200 [F200] and 250 [F250] milliseconds) normalized to body mass (N·kg^{-1}). Subjects were defined into positions by the team coaching staff, thus allowing comparisons between female youth netball players per their position. The positions were classified as: defenders (n = 14; goal keeper and goal defense), centers (n = 22; center, wing attack and wing defense) and shooters (n = 14; goal attack and goal shooter).

On arrival, all subjects had their height (Stadiometer; Seca, Birmingham, United Kingdom) and body mass assessed (Seca Digital Scales, Model 707) while in bare feet, measured to the nearest 0.1 kg and 0.01 m, respectively, and subsequently used to estimate maturity offset (Mirwald et al., 2002). Before testing, subjects performed a standardized warm-up, consisting of 10 body weight squats, 10 forward and 10 reverse lunges, and 5 submaximal countermovement jumps. All subjects rested the day before testing and were asked to attend testing in a fed and hydrated state, similar to their normal practices before training. All subjects were familiar with the tests performed in this study as part of their normal training and monitoring regime, yet further warm-up trials were performed before commencing maximal effort trials, as described below.

2.3. Isometric mid-thigh pull testing

For the IMTP, previously described procedures were used (Comfort et al., 2019). Briefly, using a portable IMTP rig (Fitness Technologies, Perth, Australia), an immovable cold rolled steel bar was positioned at a height that replicated the start of the second pull phase of the clean for each individual, with the bar fixed above the force platform to accommodate subjects of different sizes and proportions. This posture resulted in knee and hip angles of 125.3 ± 6.6° and 143.7 ± 8.4°, respectively (Comfort et al., 2019; Dos' Santos, Thomas, et al., 2017). Each subject performed 3 warm-up trials, one at 50%, one at 75%, and one at 90% of the subject's perceived maximum effort, each separated by 1 minute of rest. Once body position was stabilized (verified by watching the subject and force trace), the subjects were given a countdown of "3, 2, 1, Pull." Any obvious pretension was not permitted before initiation of the pull, with the instruction to pull against the bar "and push the feet into the ground as fast and hard as possible" which has previously been reported to produce optimal testing results (Halperin et al., 2016). Each IMTP trial was performed for approximately 5 seconds, and all subjects were given strong verbal encouragement during each trial. Subjects performed 3 maximal IMTP trials interspersed with 2 minutes of rest between trials.

Vertical ground reaction force data for the IMTP was collected using a portable force platform sampling at 1,000 Hz (9286AA, Kistler Instruments, Winterthur, Switzerland), interfaced with a laptop computer and specialist software (Bioware 3.1; Kistler Instruments) that allows for direct measurement of force-time characteristics. Raw unfiltered, force-time data was exported for subsequent analysis in a bespoke Microsoft Excel spreadsheet (version 2016, Microsoft Corp., Redmond, WA, USA). The maximum forces recorded from the force-time curve during the IMTP trials were reported as PF and subsequently ratio scaled (force / body mass [N·kg^{-1}]). The onset of force production was defined as an increase in force greater than 5 SDs of force during the one-second period of quiet standing (Dos' Santos, Jones, et al., 2017), and subsequently force at 50- (F50), 100- (F100), 150- (F150), 200- (F200), and 250 ms (F250) were also determined and ratio scaled (N·kg^{-1}). The best performance of the three trials was used for further analysis

2.4. Statistical Approach

Data are presented as either mean ± SD or mean with 95% confidence intervals (95% CI) where specified. Within-session reliability of dependent variables was examined using the intraclass correlation coefficient (ICC), typical error of measurement (TE) and coefficient of variation (CV). The magnitude of the ICC was interpreted as follows: low (<0.30), moderate (0.30–0.49), high (0.50–0.69), very high (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.0) (Koo & Li, 2016). Normality of data was confirmed by Shapiro–Wilk statistic and Q-Q plot analysis. A series of one-way analysis of variance were conducted to analyse differences in age, height, mass, maturity offset and IMTP force-time characteristics between positions. Where significant differences were found, Bonferroni post-hoc analyses were completed to detect differences between positions. The magnitude of differences between position groups was determined by calculating Hedges g effect size statistics (Hedges & Olkin, 2014), and interpreted as follows: trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), and very large (2.0–4.0) (Hopkins, 2002). All statistical analyses were completed using SPSS (version 23, IBM, New York, NY, USA). An a priori alpha level of $p \leq 0.05$ was used as the criterion for statistical significance.

3. Results

Table 1 shows reliability of all IMTP variables was high to nearly perfect (ICC = 0.68–0.90), with acceptable variability (CV = 6.49–8.94%). Briefly, there were small, nonsignificant differences (g = –0.59 to 0.27, $p = 0.110$) in age between positions, while there was a large, significant difference (g = -1.21, $p = 0.024$) in height between centers and shooters (Table 2). There were small, nonsignificant differences (g = –0.52 to 0.55, $p = 0.147$) in mass between positions, whereas there were trivial to moderate, nonsignificant differences (g = -0.55 to 0.07, $p = 0.393$) in maturity offset between positions.

Table 1: Descriptive statistics and within–session reliability measures for performance measures

Variable	Mean	SD	ICC (95% CI)	TE (95% CI)	%CV (95% CI)
Force at 50 ms (N·kg^{-1})	12.73	1.46	0.68 (0.53–0.80)	0.84 (0.73–1.00)	6.73 (5.80–8.08)
Force at 100 ms (N·kg^{-1})	14.53	1.85	0.70 (0.56–0.81)	1.16 (1.00–1.38)	8.39 (7.22–10.08)
Force at 150 ms (N·kg^{-1})	16.07	1.91	0.75 (0.63–0.84)	1.38 (1.19–1.64)	8.94 (7.70–10.75)
Force at 200 ms (N·kg^{-1})	18.67	2.30	0.82 (0.72–0.89)	1.49 (1.29–1.78)	8.38 (7.22–10.07)
Force at 250 ms (N·kg^{-1})	20.65	2.86	0.84 (0.76–0.90)	1.44 (1.25–1.72)	7.61 (6.55–9.14)
Peak Force (N·kg^{-1})	28.27	7.16	0.90 (0.85–0.94)	1.70 (1.47–2.03)	6.49 (5.59–7.78)

ICC = intraclass correlation coefficient; TE = typical error of measurement; CV = coefficient of variation; CI = confidence interval

The results of post-hoc analysis revealed a moderate, significant difference in F50 (g = -1.04, *p* = 0.025) between defenders and centers, although moderate nonsignificant differences (g = -0.69, *p* = 0.123) were observed between defenders and shooters, while small, nonsignificant differences (g = 0.22, *p* = 0.876) were found between centers and shooters. Moderate, significant differences in F100 (g = -1.14, *p* = 0.020) were revealed defenders and centers, whereas moderate, yet nonsignificant differences (g = -0.85, *p* = 0.070) were found between defenders and shooters and trivial, nonsignificant differences (g = 0.14, *p* = 0.957) were exhibited when comparing centers and shooters. There was a moderate, significant difference in F150 (g = -0.76, *p* = 0.045) between defenders and centers, yet a moderate, nonsignificant difference (g = 0.63, *p* = 0.213) between centers and shooters. Small, nonsignificant differences in F150 (g = -0.23, *p* = 0.787) were found between defenders and shooters.

Post-hoc analysis revealed nonsignificant differences in F200 (*p* = 0.088) between positions, and these differences were of a moderate effect between defenders and centers (g = -0.78, *p* = 0.072), and a small effect between both defenders and shooters (g = -0.39, *p* = 0.494), and centers and shooters (g = 0.45, *p* = 0.581). A moderate, significant difference in F250 (g = -0.84, *p* = 0.035) was revealed between defenders and centers, whereas small, nonsignificant differences were found between defenders and shooters (g = -0.54, *p* = 0.272) and centers and shooters (g = 0.27, *p* = 0.676). No significant differences in PF (*p* = 0.204) were revealed between positions, and these differences were of a moderate effect between defenders and centers (g = -0.61, *p* = 0.329) and small effect between defenders and shooters (g = -0.48, *p* = 0.210) and a trivial effect between centers and shooters (g = -0.04, *p* = 0.891).

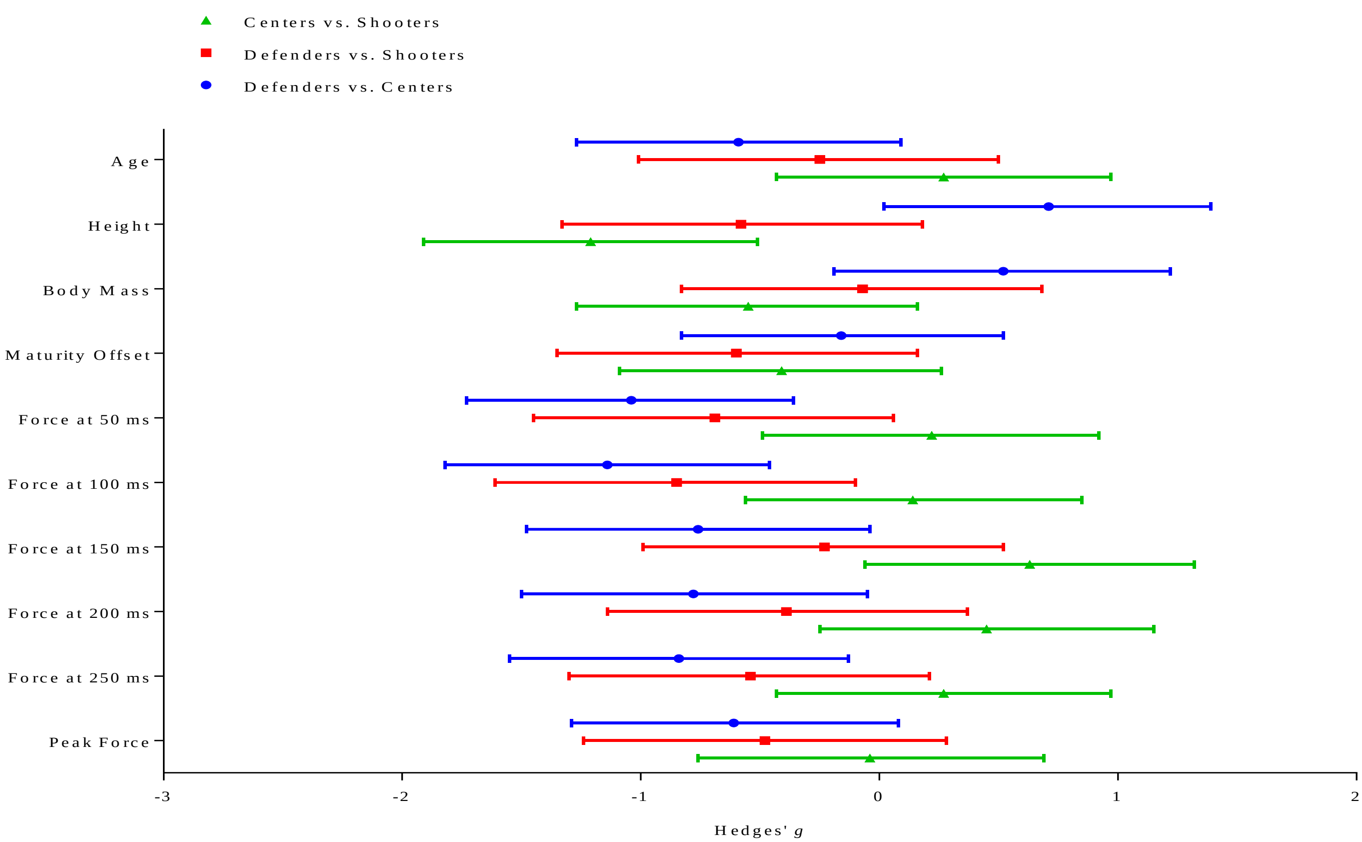

Figure 1: Hedges' g effect size differences in age, height, body mass, maturity offset and maximal isometric force-time characteristics of youth female netball players by playing position

Table 2: Age, height, body mass, maturity offset and maximal isometric force-time characteristics of youth female netball players by playing position

	Defenders (*n* = 14)	**Centers (*n* = 22)**	**Shooters (*n* = 14)**	**Defenders vs. Centers Hedges' *g***	**Defenders vs. Shooters Hedges' *g***	**Centers vs. Shooters Hedges' *g***
Age (years)	15.20 ± 1.05	15.85 ± 1.15	15.52 ± 1.34	-0.59 (-1.27 to 0.09)	-0.25 (-1.01 to 0.50)	0.27 (-0.43 to 0.97)
Height (m)	1.72 ± 0.05	1.68 ± 0.05	1.76 ± 0.07‡	0.71 (0.02 to 1.39)	-0.58 (-1.33 to 0.18)	-1.21 (-1.91 to -0.51)
Body Mass (kg)	65.83 ± 7.77	61.98 ± 5.84	66.61 ± 9.42	0.52 (-0.19 to 1.22)	-0.07 (-0.83 to 0.68)	-0.55 (-1.27 to 0.16)
Maturity Offset (years)	2.82 ± 0.70	2.95 ± 0.78	3.26 ± 0.81	-0.16 (-0.83 to 0.52)	-0.60 (-1.35 to 0.16)	-0.41 (-1.09 to 0.26)
Force at 50 ms ($N \cdot kg^{-1}$)	12.28 ± 1.23	13.66 ± 1.39†	13.35 ± 1.75	-1.04 (-1.73 to -0.36)	-0.69 (-1.45 to 0.06)	0.22 (-0.49 to 0.92)
Force at 100 ms ($N \cdot kg^{-1}$)	13.75 ± 1.70	15.84 ± 1.90†	15.58 ± 2.47	-1.14 (-1.82 to -0.46)	-0.85 (-1.61 to -0.10)	0.14 (-0.56 to 0.85)
Force at 150 ms ($N \cdot kg^{-1}$)	16.44 ± 3.01	18.53 ± 2.36†	16.99 ± 2.35	-0.76 (-1.48 to -0.04)	-0.23 (-0.99 to 0.52)	0.63 (-0.06 to 1.32)
Force at 200 ms ($N \cdot kg^{-1}$)	18.65 ± 3.97	21.31 ± 2.93	19.94 ± 3.15	-0.78 (-1.50 to -0.05)	-0.39 (-1.14 to 0.37)	0.45 (-0.25 to 1.15)
Force at 250 ms ($N \cdot kg^{-1}$)	19.99 ± 3.64	22.82 ± 3.21†	21.96 ± 3.44	-0.84 (-1.55 to -0.13)	-0.54 (-1.30 to 0.21)	0.27 (-0.43 to 0.97)
Peak Force ($N \cdot kg^{-1}$)	26.12 ± 4.05	28.79 ± 4.47	29.58 ± 7.56	-0.61 (-1.29 to 0.08)	-0.48 (-1.24 to 0.28)	-0.04 (-0.76 to 0.69)

†Significantly different ($p < 0.05$) from defenders
‡Significantly different ($p < 0.05$) from centers

4. Discussion

The aim of this study was to evaluate the IMTP force-time characteristics between position groups in youth female netball players. In agreement with our hypothesis, the results of this study indicate that moderate, significant differences in F50, F100, F150, and F250 existed between centers and defenders in youth female netball players. Yet, in contrast to our hypothesis, only trivial-to-moderate, nonsignificant differences in IMTP characteristics were observed between centers and shooters. Furthermore, trivial-to-moderate, nonsignificant differences in IMTP force-time characteristics existed between defenders and shooters. The trivial-to-moderate, nonsignificant differences in maturity offset (~0.5 years) help us to understand differences in maximal isometric force production capabilities between positions are not attributed to maturity. These findings are in agreement with previous research revealing position-specific physical profiles in academy- (Thomas et al., 2019) and state-level netballers (Graham et al., 2019). The current findings add to a growing body of literature on the physical characteristics of youth female netball players, and will serve as a basis for future studies, with the findings used to establish position-specific normative values for monitoring and assessment of youth level netball players.

In this study, center players demonstrated moderately and significantly greater F50 and F100 values compared to defenders, while shooters demonstrated moderate, nonsignificant higher values than defenders (Figure 1). Another important finding was that center players demonstrated moderately and significantly greater F150 values than defenders, and moderate, yet nonsignificant higher values compared to shooters. These findings may be explained by the fact that center players sprint, jump and change direction more often than defenders and shooters (Brooks et al., 2020; Chandler et al., 2014; Cormack et al., 2014; Graham et al., 2020); all of which are reliant upon producing high levels of force in a short period of time (Kirby et al., 2011; Spiteri et al., 2014; Weyand et al., 2010). Similarly, centers have shown to produce superior sprint, jump and change of direction performances compared to both defenders and shooters (Graham et al., 2019; Thomas et al., 2019). Considering a greater physical requirement for the center position, practitioners should allocate periods in their training programs for the development of maximal force to aid the long-term development of netball players and help prepare for the demands of training and competition.

The results of this study found small-to-moderate, nonsignificant differences in F200 amongst playing positions. In contrast, moderate, significant differences in F250 were found between centers and defenders, while small, nonsignificant differences were revealed between both defenders and shooters, and centers and shooters. It is somewhat surprising that no differences were noted in F200, yet differences were evident for F250. For all of the findings within this study it is advised practitioners interpret the data according to both statistical and practical significance. For example, findings which are statistically significant can have little practical meaning and similarly, outcomes that are not statistically significant can be practically or clinically meaningful. Moreover, magnitudes of difference with confidence limits are presented in Figure 1 to acknowledge the fact that not all changes are meaningful, and that some uncertainty always remains (Buchheit, 2017).

Trivial-to-moderate, nonsignificant differences in PF were found between positions. This finding suggests that according to our data, time-specific isometric force time characteristics may be able to better distinguish between netball playing positions, in contrast to peak values. These data must be interpreted with caution because previous studies have shown maximal isometric PF to strongly associate with sprint and change of direction time in youth female netball players (Thomas et al., 2016), while also distinguishing between superior vs. inferior sprint, jump, and change of direction performance in the same study. A recent study by Comfort et al. (2020) found greater changes in early isometric force production compared to PF in male youth soccer players, and this may partly be explained by differences between positions in inter- and intra-muscular coordination (Cormie et al., 2011), yet this was not explored in the current study. It may be that the positional demands of centers, such as increased multidirectional movement, increased player load, greater high-intensity actions and bouts (Brooks et al., 2020; Chandler et al., 2014; Graham et al., 2020), thus have to produce high levels of force in a short time, providing somewhat of a training stimulus in a variety of netball-specific tasks through training and competition. These findings may help us to understand position-specific maximal isometric force production capabilities of youth female netball players and potentially highlight the importance of developing this quality through training.

Another important finding is that, although not significantly different to other positions, shooters demonstrated the greatest PF values. Specifically, shooters revealed lower (small-to-moderate effects) F150, F200 and F250 compared to centers, but then demonstrated trivial ($g = 0.04$) differences to centers in PF values. It may be the case therefore, that there may be a window for further development of time-specific force production capabilities in shooters. This finding may have implications for monitoring maximal isometric force–time characteristics in relation to position-specific sporting movements, to evidence the planning of training drills and assist practitioners in devising periodized training programs.

A limitation of this study is that only one level of netball was examined. Previous research has found differences in physical demands between playing standards, (Cormack et al., 2014); thus, it is unknown whether the results of this study are transferrable to other populations (i.e. the professional or elite level). This study failed to record body composition measures for all subjects, thus it is unknown whether body fat levels may have contributed to differences in maximal and time-specific IMTP force production capabilities. In future investigations, it might be possible to examine the influence of body fat and body mass on IMTP force-time characteristics in youth female netball players. Notwithstanding these limitations, the study suggests that players within the current study were of similar chronological age, training age and status, and maturity status; and thus, can be considered a homogenous cohort.

In conclusion, this study achieved its major aim of identifying differences in the maximal isometric force production capabilities between position groups of youth female netball players.

Practitioners may utilise the results of this study for assisting in the creation of position-specific programs, whilst providing normative data when assessing maximal isometric force production capabilities in this population. In-line with previous studies (Graham et al., 2019; Thomas et al., 2019), the findings of this study indicate that centers exhibit greater maximal isometric force production capabilities compared to other positions. These differences could be attributed to both playing position and an individual's fitness. Such information regarding the maximal isometric force production capabilities of youth female netball players may be used by practitioners to individualize training programs to meet the physical requirements for playing positions. Indeed, center court players may need to complete more position-specific training to ensure they are meeting the demands of the playing position. Practitioners should consider developing their netball player's peak and rapid force production capabilities, while considering the specific demands on individual positions (Graham et al., 2019; Thomas et al., 2019). Further research should identify the importance of maximum strength in youth female netball players so that more specific training recommendations can be provided with regards to this capacity.

Conflict of Interest

The authors declare no conflict of interests.

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Is athletic performance affected following concussion? A systematic review and meta-analysis of literature

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ABSTRACT

Emerging research has studied in-game metrics of athletes after returning from concussion injury in an attempt to determine if performance is compromised. The aim of this meta-analysis was to quantify performance metrics in professional athletes prior to and following recovery from concussion. We conducted systematic literature searches in databases: PubMed, SCOPUS, and SPORTDiscus, between January 1990 to July 2020. Meta-analyses compared, first, pre- versus post-concussion performance within concussed athletes, and second, performance between concussed and non-concussed athletes. After thorough review, seven studies presenting pre-/post-concussion performance were retrieved. The quality of studies analysed were rated as moderate to good. Meta-analyses showed no within-group differences in performance variables in athletes following a concussion. Between group analyses showed significant differences between groups post-concussion for some variables (e.g., scoring, contribution to scoring and blocks); however, pre-concussion comparisons between groups also revealed significant differences. Collectively, our data reports no changes in athlete performance when returning to competition after suffering a concussion injury. While athletic performance appears to be affected in some variables, the retrospective nature and quasi-experimental observational designs of the studies makes interpretation difficult. However, despite study limitations, future research in this area should continue, as concussion in sport is not only a medical concern, but also a concern for high performance staff who are unsure how to work with post-concussed athletes following medical clearance to train and compete.

1. Introduction

Concussion is a growing public health and sport participation issue, particularly in contact sports where it affects individuals from youth to elite level competition (Musumeci, Ravalli, Amorini, & Lazzarino, 2019). Of particular interest is the growing understanding of the long-term changes that result from athletes sustaining repetitive head impacts during their career, including chronic neurological impairments (De Beaumont et al., 2009; Pearce et al., 2014; Pearce, Rist, Fraser, Cohen, & Maller, 2018), movement disorders (Ozolins, Aimers, Parrington, & Pearce, 2016), and neurodegenerative disease (Buckland et al., 2019; Ling et al., 2017; Mez et al., 2017; Pearce et al., 2020). To improve identification and effective return-to-play following concussion (in an attempt to minimise the long-term effects), research currently focuses on quantifying short-term changes and recovery from concussion via various neurological tests.

The neurometabolic alterations following concussion are well described (Giza & Hovda, 2001, 2014). A wide range of molecular alterations, including mitochondrial dysfunction, energy deficit, and gene and protein expression changes, are triggered by concussion and last longer than clinical symptoms (Lazzarino et al., 2019). Therefore, quantifying athlete performance post-concussion has traditionally relied on measuring various aspects of brain function. Time-course changes in saccadic eye movements and eye tracking (Galetta et al., 2016; Nguyen, King, & Pearce, 2019), vestibular and balance performance (Valovich McLeod & Hale, 2015), dual task and gait stability (Caplan et al., 2016), neurosensory processing speed (Pearce, Tommerdahl, & King, 2019; Tommerdahl et al., 2016), and neurocognitive and neurophysiological assessment (Pearce et al., 2015), all show negative effects following concussion and

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with varying rates of recovery. While research in this area has provided insights into brain dysfunction and recovery following a concussion (Giza & Hovda, 2001, 2014), allowing for clinical return-to-play decisions, translation to post-concussion on-field athletic performance remains unknown (Parrington et al., 2019). This information may play an important role in understanding the effects of concussion beyond current clinical testing and may aid in assessing recovery from concussion in applied performance settings.

While the majority of research on athlete outcomes has concentrated on clinical and neuropsychological factors, there is increased interest in post-concussion effects on subsequent injury risk and in-game performance. Some studies report that athletes are at an increased risk of musculoskeletal injury following a concussion (Brooks et al., 2016; Herman et al., 2017; McPherson, Shirley, Schilaty, Larson, & Hewett, 2020; Nordström, Nordström, & Ekstrand, 2014), although this risk has recently been challenged (Shrier, Piché, & Steele, 2019), while the effect on performance is unclear. Despite medical clearance, understanding whether players are at an increased risk of injury or potentially have poorer on-field performance, for example scoring goals, assists, disposal efficiency, becomes an important consideration for coaching and high-performance staff regarding appropriate team selection and performance monitoring practices. Other factors that contribute to a desirable performance, including technical and tactical proficiency, must be considered for coaching staff to make an informed decision on team selection. Whether these factors are influenced by concussion, and if they have the same time course for recovery as medical clearance tests, is not well established in the literature.

A growing number of studies have explored pre- and post-concussion game metrics in an attempt to determine if athlete performance is compromised after a concussion (Hardy, Jordan, Wolf, Johnson, & Brand, 2017; Kuhn, Zuckerman, Totten, & Solomon, 2016; Kumar et al., 2014; Makdissi, McCrory, Ugoni, Darby, & Brukner, 2009; Reams, Hayward, Kutcher, & Burke, 2017; Wasserman, Abar, Shah, Wasserman, & Bazarian, 2015; Yengo-Kahn et al., 2016; Zuckerman et al., 2018). For example, in soccer, Hardy et al. (2017) found a significant reduction in attempts on goal and total attempts on goal per season after concussion. Makdissi et al. (2009) quantified passing the ball (through kicks and handballs) in Australian football players after they had a concussion, showing no change post-concussion. In bat and ball sports such as baseball, Wasserman et al. (2015) has investigated batting performance pre- and post-concussion. To gain a more holistic view of performance related changes following concussion, we completed a systematic review and meta-analysis to determine whether athletes who have been cleared to return to play after their concussion perform worse compared with non-concussed athletes, and whether athletes show performance decrements after concussion compared with their pre-concussion performance. Based on traditional studies investigating neurological deficits post-concussion, and the apparent risk of musculoskeletal injury, we hypothesised that athletes who had sustained a concussion would: 1) demonstrate worse performance post-concussion when compared to their pre-concussion on-field metrics (within-group comparison), and 2) show poorer metrics following concussion when compared with non-injured (control) athletes (between group comparison).

Table 1: Medline search strategy (modified from Manley et al., 2017)

Concussion term	**Sport terms**	**Performance terms**
Brain Concussion (MeSH) OR concuss* OR sport* related concuss* OR Brain Injuries (MeSH) OR Brain Injury OR Craniocerebral Trauma (MeSH) OR mtbi OR traumatic brain injur*	Athletes (MeSH[1]) OR Sports (MeSH) OR Baseball (MeSH) OR Boxing (MeSH) OR Bicycling (MeSH) OR Diving (MeSH) OR Football (MeSH) OR Hockey (MeSH) OR Racquet Sports (MeSH) OR Martial Arts (MeSH) OR Mountaineering (MeSH) OR Skating (MeSH) OR Skiing (MeSH) OR Snow Sports (MeSH) OR Soccer (MeSH) OR Wrestling (MeSH) OR athlete* OR player* OR rider* OR cyclist* OR boxer* OR skater* OR skier* OR wrestler* OR sport* OR athletic* OR football OR hockey OR skating OR rugby OR lacrosse OR soccer OR baseball OR boxing OR bmx OR bicycling OR cycling OR biking OR diving OR equestrian OR equine OR racket sport* OR racquet sport* OR tennis OR squash OR racquetball OR martial arts OR judo OR tae kwon do OR mountaineering OR climbing OR skiing OR snowboard* OR ski jump* OR ski racing OR bobsled* OR toboggan* OR wrestling OR contact sport* OR softball OR handball	Athletic Performance (MeSH) OR Return to Sport (MeSH) OR performance or professional athletes

[1]MeSH terms were exploded to include more specific terms; MeSH terms were translated into the appropriate subject headings for other databases. Keywords were the same for each database searched.

2. Methods

2.1. Literature Search Strategy

A standardised search strategy used the following electronic databases: PubMed/MEDLINE, SCOPUS, and SPORTDiscus from 1 January 1990 until 31 March 2020. Medical Subject Headings (MeSH) or keywords and matching synonyms were combined (Table 1 illustrates key words and search strategy) (Manley et al., 2017). References found from previously published literature were also searched.

2.2. Inclusion and Exclusion Criteria

The inclusion and exclusion criteria followed the Population – Indicator – Comparator – Outcome (PICO) principle (Wright, Brand, Dunn, & Spindler, 2007) to identify studies relevant to our research hypothesis. Studies in English of adults (males and females ≥18 years) involved in professional sports in which data collection methods for every player during every competitive match are well established (Zuckerman et al., 2018). Non-human studies and studies involving under-age adults (<18 years) were excluded. Studies of unspecified brain injury or moderate, severe or unspecified traumatic brain injury were excluded. Studies were required to have reported data with a pre-concussion and post-concussion and/or comparison control group. Pre-concussion measurement for within-participants comparison, and between-participants comparator, was required as a comparator for inclusion. Case studies, case reports, non-peer reviewed journal papers, conference abstracts, undergraduate (e.g., honours) or post-graduate (e.g., Masters/PhD) theses, and narrative reviews and descriptive studies without presentation of data were excluded.

Figure 1 outlines the flow of studies removed following the application of each criterion according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher, Liberati, Tetzlaff, & Altman, 2009; Moher et al., 2015). While commonly used to report on randomised trials, PRISMA has been used to systematically review quasi-experimental research (Moher et al., 2009).

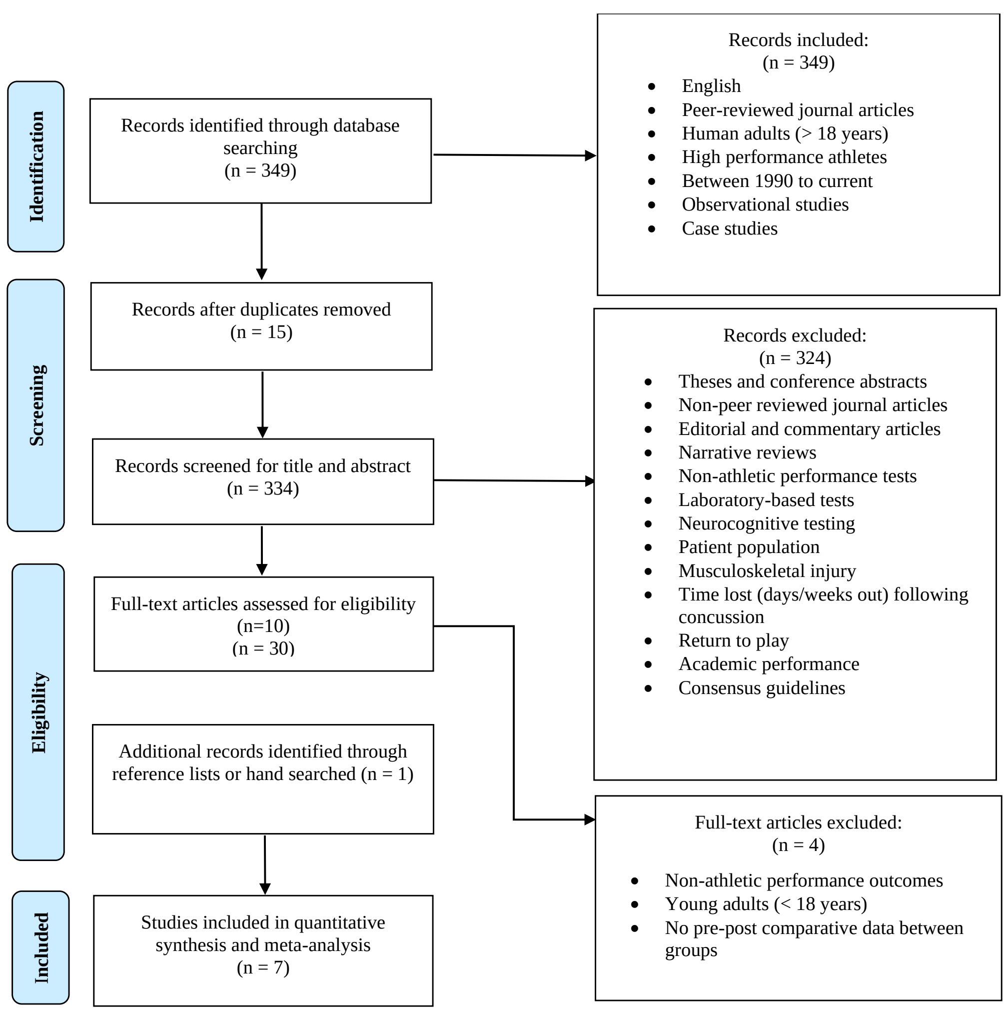


Figure 1: Flow of identification, screening, eligibility and study inclusion of previously published studies using the PRISMA guidelines

2.3. Selection of Studies and Quality Assessment

Two authors (KM and AJP) evaluated the title and abstracts of the articles against inclusion and exclusion criteria. Any titles not relating to the topic were also excluded. Lack of agreement regarding title and abstracts from the first pass of the review were resolved by mutual agreement with the third author (AC). Following duplication, article full texts were then obtained for data extraction. Study quality was assessed by two authors (AJP and KM) using a modified Downs and Black (1998) quality checklist (Pearce et al., 2012), similar to previous systematic reviews (Kidgell, Bonanno, Frazer, Howatson, & Pearce, 2017; Morris et al., 2013; Pearce et al., 2012). The Downs and Black quality checklist is specifically designed to assess the quality of both randomised and non-randomised studies. The revised checklist includes a 20-question checklist and quality is as previously reported (Hooper, Jutai, Strong, & Russell-Minda, 2008) for excellent $\geq$16; good (13-15); moderate (9-14); and poor $\leq$8 studies. Lack of agreement about inclusion of articles or grading against study quality was reconciled by mutual agreement with all other authors. Articles that satisfied the inclusion criteria were read and eligible studies were then included in the meta-analysis.

2.4. Data Extraction and Analyses

For all included articles, data extraction involved the retrieval of study characteristics (author, year, sample size, and study design), athlete demographics (age, gender), and the category of sport analysed (team, bat and ball, ice sport). This was completed by one author (AJP) with a sub sample checked by two other authors (AC and KM). Table 2 outlines the metrics extracted that were included in the meta-analysis.

Data (mean and SD) were extracted from tables presented in studies. If studies contained data in a graphical rather than in a tabulated format, Plot Digitizer (Version 2.6) was used to extract the charted data.

2.5. Statistical Analysis

Pre- and post-concussion data were compared within group (concussed athletes only) and between groups (concussed versus control athletes) for each study. As systematic influences and random error were predicted to be present between study level effect sizes, a random effects meta-analysis was performed to compare the overall pooled standardised mean differences (SMDs) for the main outcome measures (Borenstein, Hedges, Higgins, & Rothstein, 2010). SMDs with 95% confidence intervals (CIs) were used to measure concussion effects on performance as the included studies presented outcome measures in a variety of ways. The absolute SMD values of < 0.5 (small), 0.50 - 0.79 (moderate), and ≥ 0.80 (large) were used to describe the magnitude of effects (Cohen, 1988). Heterogeneity was measured using the I^2 statistic, indicating the percentage variance between studies for low (25%), moderate (50%) and high (75%) heterogeneity (Higgins, Thompson, Deeks, & Altman, 2003). All statistical analyses were conducted using RevMan (V5.3, Review Manager, The Cochrane Collaboration) using a significance level of $\alpha = 0.05$.

Table 2: Metric variables, including grouped variables (except blocks, turnovers, or fouls which were presented as individual variables), and operational definition for each metric used.

Metric		Operational Definition
Scoring/contribution to scoring	Goals	Method of scoring for the athlete or team. Includes *home run* (Wasserman et al., 2015) and *touch down* (Kumar et al., 2014; Reams et al., 2017).
	Shots on goal	Scoring chance that does not result in successful outcome.
	Assists	Attributed to teammates who passed the object prior to goal.
Player evaluation measures	Time played	The time (in minutes or seconds) when a player is involved in the match.
	Plus/minus	An athlete's impact on the game, represented by the difference between their team's total scoring versus their opponent's when the player is in the game.
	Player ratings	Arbitrary score, calculated through sport specific characteristics of the individual's performance in each match.
Ungrouped measures	Blocks	Halting or impeding the progress or movement of the object (e.g., ball or puck) by the opposing player.
	Turnovers	Player or team loses possession of the object (e.g., ball or puck) to the opposing team.
	Fouls	Inappropriate or unfair act by a player as deemed by a referee, usually violating the rules of a sport or game.

Table 3: Characteristics of studies meeting inclusion criteria, Downs and Black (1998) score and NHMRC level of evidence.

Author(s)	Country	Sport	Sample size and athlete characteristics	Mean age (± SD)	Key findings	Downs and Black (1998) Score	% of max score
Hardy et al. 2017	USA	MLS	Concussion: 37 males Controls: 73 males	n/a	Players who were diagnosed with concussion showed reduced performance, defined as decreased shots on goal and reduced time played compared to non-concussed controls.	13	65
Kuhn et al. 2016	USA	NHL	Concussion: 94 males Controls: 58 males	25.5 ± 5.0 years 27.5 ± 3.8 years	No difference in performance or time on ice between concussed players who returned to play versus controls.	13	65
Kumar et al. 2014	USA	NFL	Concussion: 59 males Controls: 72 males	25.9 ± 4.2 years 27.2 ± 3.2 years	No difference in performance between concussed players who returned to play versus controls. Playing experience and timing of injury within the course of the season showed strong associations with return to play within 7 d after concussion.	14	70
Reams et al. 2017	USA	NFL	Concussion: 140 males Controls: 57 males	n/a	Concussed players performed at their baseline level of performance suggesting that players had recovered from concussion. However, comparison between groups pre concussion, showed concussed players' performance was worse than controls,	11	55
Wasserman et al. 2015	USA	MLB	Concussion: 66 males Controls: 68 males	n/a	Compared to control athletes, concussed players showed reduced performance measures for batting.	14	70
Yengo-Kahn et al. 2016	USA	NBA	Concussion: 51 males Controls: 51 males	25.6 ± 3.9 years 28.6 ± 3.7 years	No difference between concussed players versus controls. No change in performance in concussed players prior to, versus post concussion injury.	14	70
Buckley et al. 2019	USA	NHL	Concussion: 93 males Controls: 51 males	27.5 ± 5.0 years 27.5 ± 3.8 years	No significant differences between concussed players vs controls across all measures.	14	70

MLS: Major League Soccer; NHL: National Hockey League; NFL: National Football League; MLB: Major League Baseball; NBA: National Basketball League; N/a: mean age/SD age not presented in paper. * Modified form of quality assessment employed to account for observational studies (maximum score 20).

3. Results

3.1. Summary of Included Studies

The initial search yielded 349 records based on title and abstract. Following removal of duplicates (n = 15), the remaining 334 records were screened with 324 removed because they did not meet the inclusion criteria. Ten full-text papers were assessed for eligibility, with four of these being removed for reasons including presenting laboratory-based cognitive outcomes only, non-adult sample, and no pre-post comparative data presented (Figure 1). Further searching of reference lists and hand searching revealed one record meeting the inclusion criteria, making the final total of seven studies.

Included studies are shown in Table 3. Quality assessment scores for studies ranged from 11 to 14 (Downs & Black, 1998). It should be noted that as retrospective observational case-control studies, several criteria were not applicable, such as randomisation of study participants, likely affecting the already modified criteria. All participants included in the data were male.

3.2. Within Group Comparison for Pre- versus Post-concussion

The overall pooled data for *scoring/contribution to scoring* (Figure 2, n = 1008) showed small changes following a concussion (overall SMD = 0.07 [CI: -0.03 - 0.17]; I^2 = 27%; P = 0.19). Subgroup analyses showed small effects but non-significant differences for *goals* (SMD = 0.03; P = 0.80), *shots on goal* (SMD = 0.11; P = 0.17), and *assists* (SMD = 0.09; P = 0.43). Heterogeneity ranged from low (0%) for *shots on goal* to moderate (48%) for *assists* and *goals*.

Within group comparison data for *player evaluation* are shown in Figure 3. Overall pooled data (n = 824) showed no significant change (SMD = -0.02 [CI: -0.12 - 0.08]; P = 0.68) and low heterogeneity (0%). Subgroup analyses similarly showed no change for *player ratings* (SMD = -0.07; P = 0.42), *time played* (SMD = 0.08; P = 0.27), or *plus/minus* (SMD = -0.11; P = 0.29). Heterogeneity ranged from low (0%) to moderate (19%).

Figure 4(a-c) illustrates the separate variables of *blocks* (n = 145), *turnovers* (n = 145), and *fouls* (n = 238) respectively. No changes were observed for any of the variables and heterogeneity was small (0%).

3.3. Between Groups Comparison for Concussed Players versus Controls

Between group data for *scoring/contributing to scoring* are illustrated in Figure 5 (a and b). Overall pooled data showed a small difference between the concussed (n = 1008) and control (n = 888) groups in both pre (Figure 5a; SMD = -0.15 [CI:-0.26 – -0.05]; P = 0.005) and post (Figure 5b; SMD = -0.18 [-0.32 – -0.04]; P = 0.01) concussion. Heterogeneity ranged from low (24%) to moderate (55%) for pre- and post-concussion respectively.

Subgroup analyses for *goals* revealed a significant difference between groups pre (SMD = -0.21 [CI: -0.43 – 0.00]; I^2 = 43%; P = 0.05) and post (SMD = -0.22 [CI: -0.38 – -0.06]; I^2 = 0%; P = 0.008) concussion. No significant differences were observed between the concussed and control groups for pre- or post-concussion SMD for *shots on goals* or *assists* (Figures 5a and b).

Between groups data for *player evaluation* are presented in Figure 6 (a and b). Overall pooled data showed non-significant differences between the concussed (n = 824) and control (n = 636) groups in both pre (Figure 6a; SMD = 0.06 [CI: -0.05 – 0.16]; P = 0.28) and post (Figure 6b; SMD = 0.10 [-0.06 – 0.26]; P = 0.21) concussion outcomes. Heterogeneity ranged from low (0%) to moderate (55%) for pre- and post-concussion respectively.

Subgroup analyses for *player ratings and plus/minus* revealed no differences between groups pre- or post-concussion. Concussed players were observed to have a greater amount of time played pre-concussion compared to controls (SMD = 0.17; P = 0.04). Conversely, comparison on time played between groups was not significantly different post-concussion (SMD = 0.06; P = 0.56).

Due to disparity in metrics, *blocks*, *turnovers* and *fouls* are presented as separate variables, comparing the concussed (n = 145) and control groups (n = 109), in Figures 7 – 9.

Blocks (Figure 7a and b) showed small differences between groups in both pre (SMD = 0.39 [CI: 0.13 – 0.64]; I^2 = 0%; P = 0.003) and post (SMD = 0.43 [CI: 0.18 – 0.69]; I^2 = 0%; $P < 0.001$) concussion. *Turnovers* (Figure 8a and b) showed no differences between groups for pre (SMD = 0.07 [CI: -0.18 – 0.32]; I^2 = 0%; P = 0.58) or post (SMD = 0.23 [CI: -0.02 – 0.48]; I^2 = 0%; P = 0.07) concussion. Similarly, *fouls* (Figure 9a and b) showed no differences between groups (concussed n = 238; control n = 160) pre- or post-concussion, with moderate to large heterogeneity (pre: SMD = 0.08 [CI: -0.19 – 0.36]; I^2 = 45%; P = 0.56; post: SMD = 0.42 [CI: -0.49 – 1.32]; I^2 = 95%; P = 0.37).

4. Discussion

This systematic review and meta-analysis aimed to assess the literature relating to the question of whether athletic performance was affected following a concussion. In the past five years, a number of studies have reported increased musculoskeletal injury risk in athletes following a concussion injury (Brooks et al., 2016; Herman et al., 2017; McPherson et al., 2020; Nordström et al., 2014). Similarly, studies over the same time period have aimed to determine if concussion injury affects an athlete's subsequent on-field performance; yet this aspect of concussion has been less widely discussed, and is the *raison d'etre* for this meta-analysis.

Our study findings, while needing to take into account that data was analysed independent of contextual factors such as playing environment, opposition traits, and phase of season, showed that while within-group comparison of pre and post-concussion metrics did not change, there were differences between groups. Interestingly, between group differences were found in both pre- and post-concussion metrics.

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
Goals								
Buckley et al	0.08	0.14	93	0.1	0.2	93	8.6%	-0.12 [-0.40, 0.17]
Hardy et al - goals	2.73	4.33	37	1.78	2.92	37	4.3%	0.25 [-0.20, 0.71]
Kuhn et al - goals	0.55	0.88	94	0.71	1.3	94	8.6%	-0.14 [-0.43, 0.14]
Wasserman et al - goals	3.06	3.28	61	1.86	2.84	61	6.3%	0.39 [0.03, 0.75]
Yengo-Kahn et al - goals	10.16	5.1	51	10.84	5.73	51	5.6%	-0.12 [-0.51, 0.26]
Subtotal (95% CI)			**336**			**336**	**33.3%**	**0.03 [-0.19, 0.24]**
Heterogeneity: Tau² = 0.03; Chi² = 7.68, df = 4 (P = 0.10); I² = 48%								
Test for overall effect: Z = 0.25 (P = 0.80)								
Shots on goals								
Buckley et al	1.33	0.74	93	1.32	0.75	93	8.6%	0.01 [-0.27, 0.30]
Hardy et al - shots on goal	9.46	11.74	37	6.52	8.95	37	4.3%	0.28 [-0.18, 0.74]
Kuhn et al - shots on goal	8.6	5	94	8.5	5.2	94	8.7%	0.02 [-0.27, 0.31]
Wasserman et al - shots on goal	0.71	0.24	61	0.63	0.24	61	6.3%	0.33 [-0.03, 0.69]
Yengo-Kahn et al - shots on goal	5.32	3.01	51	5.19	3.05	51	5.6%	0.04 [-0.35, 0.43]
Subtotal (95% CI)			**336**			**336**	**33.4%**	**0.11 [-0.05, 0.26]**
Heterogeneity: Tau² = 0.00; Chi² = 2.92, df = 4 (P = 0.57); I² = 0%								
Test for overall effect: Z = 1.37 (P = 0.17)								
Assists								
Buckley et al	0.18	0.2	93	0.21	0.21	93	8.6%	-0.15 [-0.43, 0.14]
Hardy et al - assists	1.99	1.55	37	1.48	1.9	37	4.3%	0.29 [-0.17, 0.75]
Kuhn et al - assists	1.4	1.4	94	1.4	1.3	94	8.7%	0.00 [-0.29, 0.29]
Wasserman et al - assists	0.32	0.09	61	0.28	0.09	61	6.3%	0.44 [0.08, 0.80]
Yengo-Kahn et al - assists	2.26	2.34	51	2.35	2.65	51	5.6%	-0.04 [-0.42, 0.35]
Subtotal (95% CI)			**336**			**336**	**33.3%**	**0.09 [-0.13, 0.30]**
Heterogeneity: Tau² = 0.03; Chi² = 7.67, df = 4 (P = 0.10); I² = 48%								
Test for overall effect: Z = 0.79 (P = 0.43)								
Total (95% CI)			**1008**			**1008**	**100.0%**	**0.07 [-0.03, 0.17]**
Heterogeneity: Tau² = 0.01; Chi² = 19.11, df = 14 (P = 0.16); I² = 27%								
Test for overall effect: Z = 1.32 (P = 0.19)								
Test for subgroup differences: Chi² = 0.34, df = 2 (P = 0.84), I² = 0%								

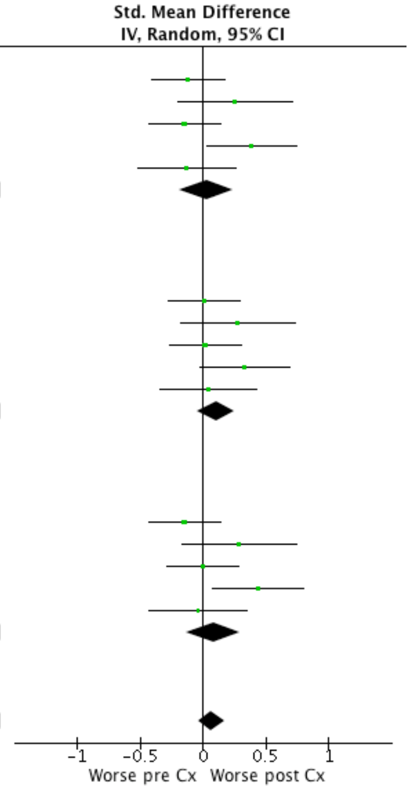


Figure 2: Scoring/contribution to scoring variables for concussed athletes' pre and post injury

Study or Subgroup	Pre Mean	Pre SD	Pre Total	Post Mean	Post SD	Post Total	Weight	Std. Mean Difference IV, Random, 95% CI
Player ratings								
Kumar et al - player ratings	-0.06	2.2	59	0.1	0.09	59	7.2%	-0.10 [-0.46, 0.26]
Reams et al - DYAR	0.26	7.55	140	0.76	4.06	140	17.0%	-0.08 [-0.32, 0.15]
Yengo-Kahn et al - player impact	8.54	4.52	51	8.59	4.87	51	6.2%	-0.01 [-0.40, 0.38]
Subtotal (95% CI)			**250**			**250**	**30.4%**	**-0.07 [-0.25, 0.10]**
Heterogeneity: Tau² = 0.00; Chi² = 0.13, df = 2 (P = 0.94); I² = 0%								
Test for overall effect: Z = 0.81 (P = 0.42)								
Time played								
Buckley et al	13.65	2.87	93	13.55	2.84	93	11.3%	0.03 [-0.25, 0.32]
Hardy et al - time played	1,503	554.04	37	1,203	820.61	37	4.4%	0.42 [-0.04, 0.89]
Kuhn et al - time played	5,193.3	1,321.9	94	5,085	1,260.8	94	11.4%	0.08 [-0.20, 0.37]
Wasserman et al - plate appearances	40.72	14.37	61	38.64	15.67	61	7.4%	0.14 [-0.22, 0.49]
Yengo-Kahn et al - time played	27.02	8.14	51	28.04	7.82	51	6.2%	-0.13 [-0.52, 0.26]
Subtotal (95% CI)			**336**			**336**	**40.8%**	**0.08 [-0.07, 0.24]**
Heterogeneity: Tau² = 0.00; Chi² = 3.42, df = 4 (P = 0.49); I² = 0%								
Test for overall effect: Z = 1.09 (P = 0.27)								
Plus/minus								
Buckley et al	0.09	1.98	93	0.3	2.14	93	11.3%	-0.10 [-0.39, 0.19]
Kuhn et al - plus/minus	-0.07	2.6	94	0.57	2.3	94	11.3%	-0.26 [-0.55, 0.03]
Yengo-Kahn et al - plus/minus	-0.01	4.77	51	-0.68	5.73	51	6.2%	0.13 [-0.26, 0.51]
Subtotal (95% CI)			**238**			**238**	**28.8%**	**-0.11 [-0.31, 0.09]**
Heterogeneity: Tau² = 0.01; Chi² = 2.46, df = 2 (P = 0.29); I² = 19%								
Test for overall effect: Z = 1.06 (P = 0.29)								
Total (95% CI)			**824**			**824**	**100.0%**	**-0.02 [-0.12, 0.08]**
Heterogeneity: Tau² = 0.00; Chi² = 9.25, df = 10 (P = 0.51); I² = 0%								
Test for overall effect: Z = 0.42 (P = 0.68)								
Test for subgroup differences: Chi² = 2.91, df = 2 (P = 0.23), I² = 31.2%								

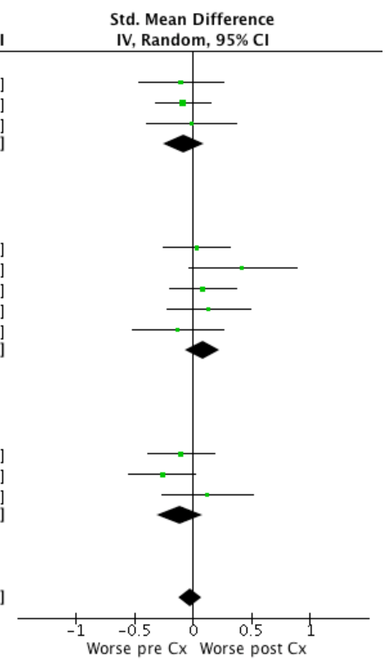


Figure 3: Player evaluation measures for concussed athletes pre and post injury

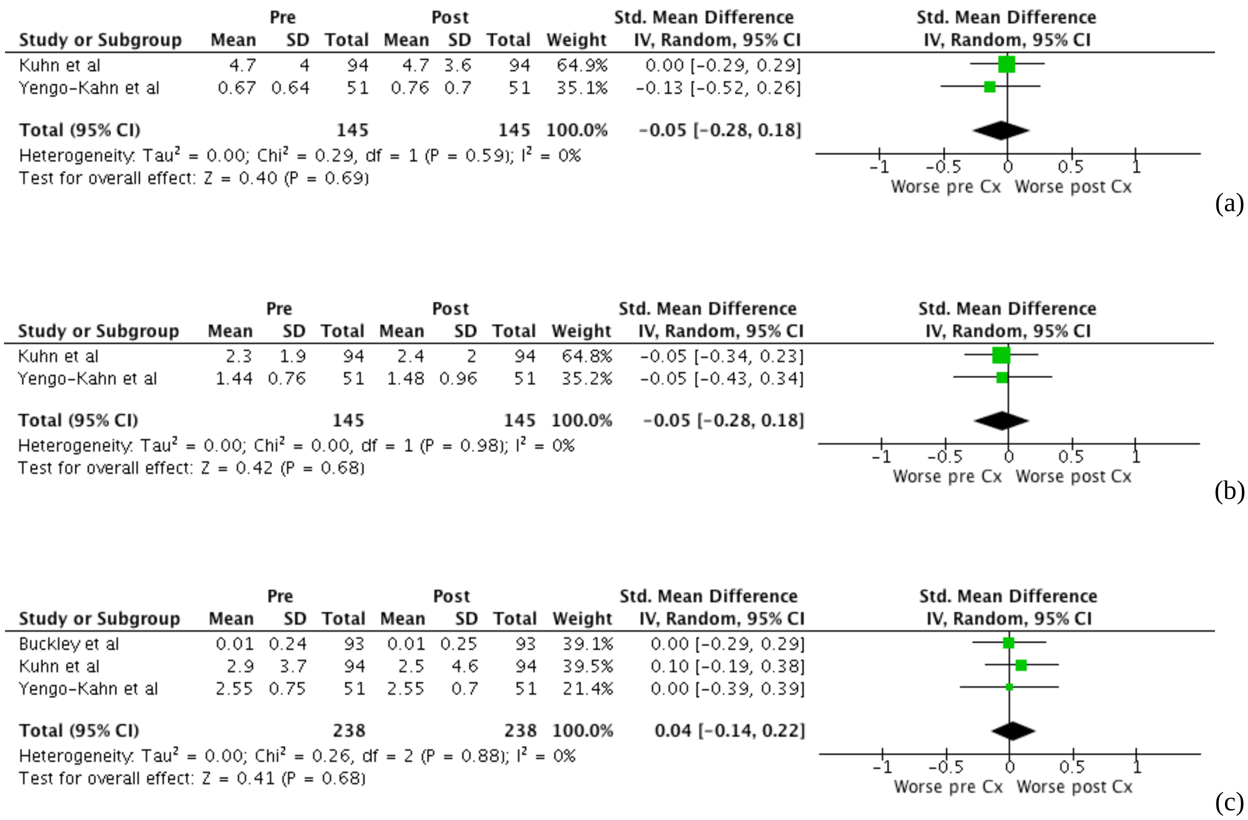
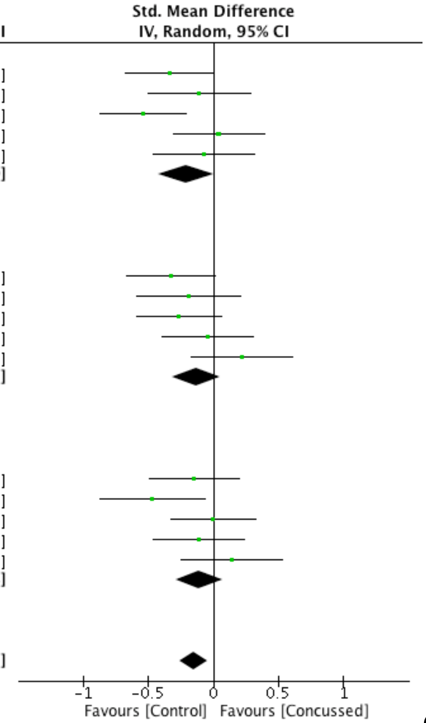


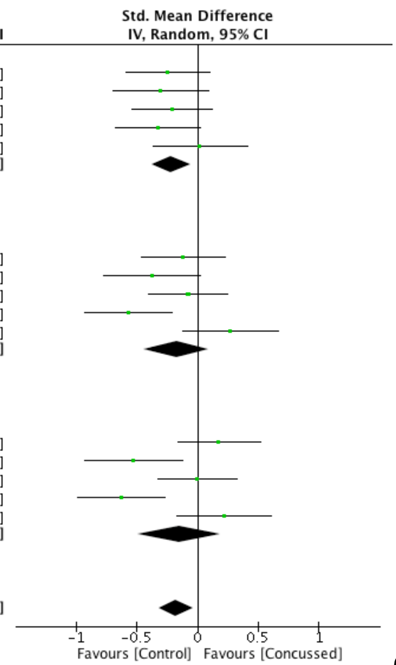
Figure 4a-c: Within-group comparison for concussed athletes' pre and post injury for blocks (a), turnover (b), fouls (c)

Study or Subgroup	Concussed Mean	Concussed SD	Concussed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Goals								
Buckley et al	0.08	0.14	93	0.13	0.16	51	7.2%	−0.34 [−0.68, 0.01]
Hardy et al	2.73	4.33	37	3.14	3.58	73	5.8%	−0.11 [−0.50, 0.29]
Kuhn et al	0.55	0.88	94	1.1	1.2	58	7.5%	−0.54 [−0.87, −0.21]
Wasserman et al	3.06	3.28	61	2.8	8.25	63	6.9%	0.04 [−0.31, 0.39]
Yengo-Kahn et al	10.16	5.1	51	10.53	5.43	51	5.9%	−0.07 [−0.46, 0.32]
Subtotal (95% CI)			**336**			**296**	**33.3%**	**−0.21 [−0.43, 0.00]**
Heterogeneity: Tau^2 = 0.03; Chi^2 = 7.00, df = 4 (P = 0.14); I^2 = 43%								
Test for overall effect: Z = 1.95 (P = 0.05)								
Shots on goals								
Buckley et al	1.33	0.74	93	1.58	0.81	51	7.2%	−0.32 [−0.67, 0.02]
Hardy et al	9.46	11.74	37	11.67	11.49	73	5.8%	−0.19 [−0.59, 0.21]
Kuhn et al	8.6	5	94	10	5.7	58	7.6%	−0.26 [−0.59, 0.06]
Wasserman et al	0.71	0.24	61	0.72	0.23	63	6.9%	−0.04 [−0.39, 0.31]
Yengo-Kahn et al	5.19	3.01	51	4.54	2.89	51	5.9%	0.22 [−0.17, 0.61]
Subtotal (95% CI)			**336**			**296**	**33.4%**	**−0.13 [−0.32, 0.05]**
Heterogeneity: Tau^2 = 0.01; Chi^2 = 5.27, df = 4 (P = 0.26); I^2 = 24%								
Test for overall effect: Z = 1.41 (P = 0.16)								
Assists								
Buckley et al	0.18	0.2	93	0.21	0.21	51	7.2%	−0.15 [−0.49, 0.20]
Hardy et al	1.99	1.55	37	3.34	3.33	73	5.7%	−0.47 [−0.87, −0.07]
Kuhn et al	1.4	1.4	94	1.4	1.6	58	7.7%	0.00 [−0.33, 0.33]
Wasserman et al	0.32	0.09	61	0.33	0.09	63	6.9%	−0.11 [−0.46, 0.24]
Yengo-Kahn et al	2.26	2.34	51	1.95	1.9	51	5.9%	0.14 [−0.24, 0.53]
Subtotal (95% CI)			**336**			**296**	**33.4%**	**−0.11 [−0.29, 0.08]**
Heterogeneity: Tau^2 = 0.01; Chi^2 = 5.20, df = 4 (P = 0.27); I^2 = 23%								
Test for overall effect: Z = 1.15 (P = 0.25)								
Total (95% CI)			**1008**			**888**	**100.0%**	**−0.15 [−0.26, −0.05]**
Heterogeneity: Tau^2 = 0.01; Chi^2 = 18.53, df = 14 (P = 0.18); I^2 = 24%								
Test for overall effect: Z = 2.79 (P = 0.005)								
Test for subgroup differences: Chi^2 = 0.56, df = 2 (P = 0.76), I^2 = 0%								



(a)

Study or Subgroup	Concussed Mean	Concussed SD	Concussed Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Goals								
Buckley et al	0.1	0.2	93	0.15	0.21	51	7.0%	−0.24 [−0.59, 0.10]
Hardy et al - goals	2.15	2.49	37	3.14	3.58	73	6.1%	−0.30 [−0.70, 0.10]
Kuhn et al - goals	0.71	1.3	94	0.97	1.1	58	7.3%	−0.21 [−0.54, 0.12]
Wasserman et al - goals	1.86	2.84	61	2.94	3.67	63	6.8%	−0.33 [−0.68, 0.03]
Yengo-Kahn et al - goals	10.84	5.73	51	10.72	5.63	51	6.3%	0.02 [−0.37, 0.41]
Subtotal (95% CI)			**336**			**296**	**33.4%**	**−0.22 [−0.38, −0.06]**
Heterogeneity: Tau^2 = 0.00; Chi^2 = 2.01, df = 4 (P = 0.73); I^2 = 0%								
Test for overall effect: Z = 2.65 (P = 0.008)								
Shots on goals								
Buckley et al	1.32	0.75	93	1.41	0.8	51	7.0%	−0.12 [−0.46, 0.23]
Hardy et al - shots on goal	7.7	8.01	37	11.67	11.49	73	6.1%	−0.38 [−0.78, 0.02]
Kuhn et al - shots on goal	8.5	5.2	94	8.9	5.5	58	7.3%	−0.07 [−0.40, 0.25]
Wasserman et al - shots on goal	0.63	0.24	61	0.77	0.25	63	6.7%	−0.57 [−0.93, −0.21]
Yengo-Kahn et al - shots on goal	5.32	3.05	51	4.48	3.06	51	6.2%	0.27 [−0.12, 0.66]
Subtotal (95% CI)			**336**			**296**	**33.3%**	**−0.17 [−0.44, 0.10]**
Heterogeneity: Tau^2 = 0.06; Chi^2 = 11.11, df = 4 (P = 0.03); I^2 = 64%								
Test for overall effect: Z = 1.26 (P = 0.21)								
Assists								
Buckley et al	0.21	0.21	93	0.17	0.25	51	7.0%	0.18 [−0.17, 0.52]
Hardy et al - assists	1.84	1.31	37	3.34	3.33	73	6.0%	−0.53 [−0.93, −0.13]
Kuhn et al - assists	1.4	1.3	94	1.4	1.3	58	7.3%	0.00 [−0.33, 0.33]
Wasserman et al - assists	0.27	0.09	61	0.33	0.1	63	6.7%	−0.63 [−0.99, −0.27]
Yengo-Kahn et al - assists	2.3	2.6	51	1.8	1.9	51	6.2%	0.22 [−0.17, 0.61]
Subtotal (95% CI)			**336**			**296**	**33.3%**	**−0.15 [−0.49, 0.19]**
Heterogeneity: Tau^2 = 0.12; Chi^2 = 17.79, df = 4 (P = 0.001); I^2 = 78%								
Test for overall effect: Z = 0.85 (P = 0.40)								
Total (95% CI)			**1008**			**888**	**100.0%**	**−0.18 [−0.32, −0.04]**
Heterogeneity: Tau^2 = 0.04; Chi^2 = 31.43, df = 14 (P = 0.005); I^2 = 55%								
Test for overall effect: Z = 2.49 (P = 0.01)								
Test for subgroup differences: Chi^2 = 0.17, df = 2 (P = 0.92), I^2 = 0%								



(b)

Figure 5: Scoring/contribution to scoring variables for between groups pre (a) and post (b) concussion

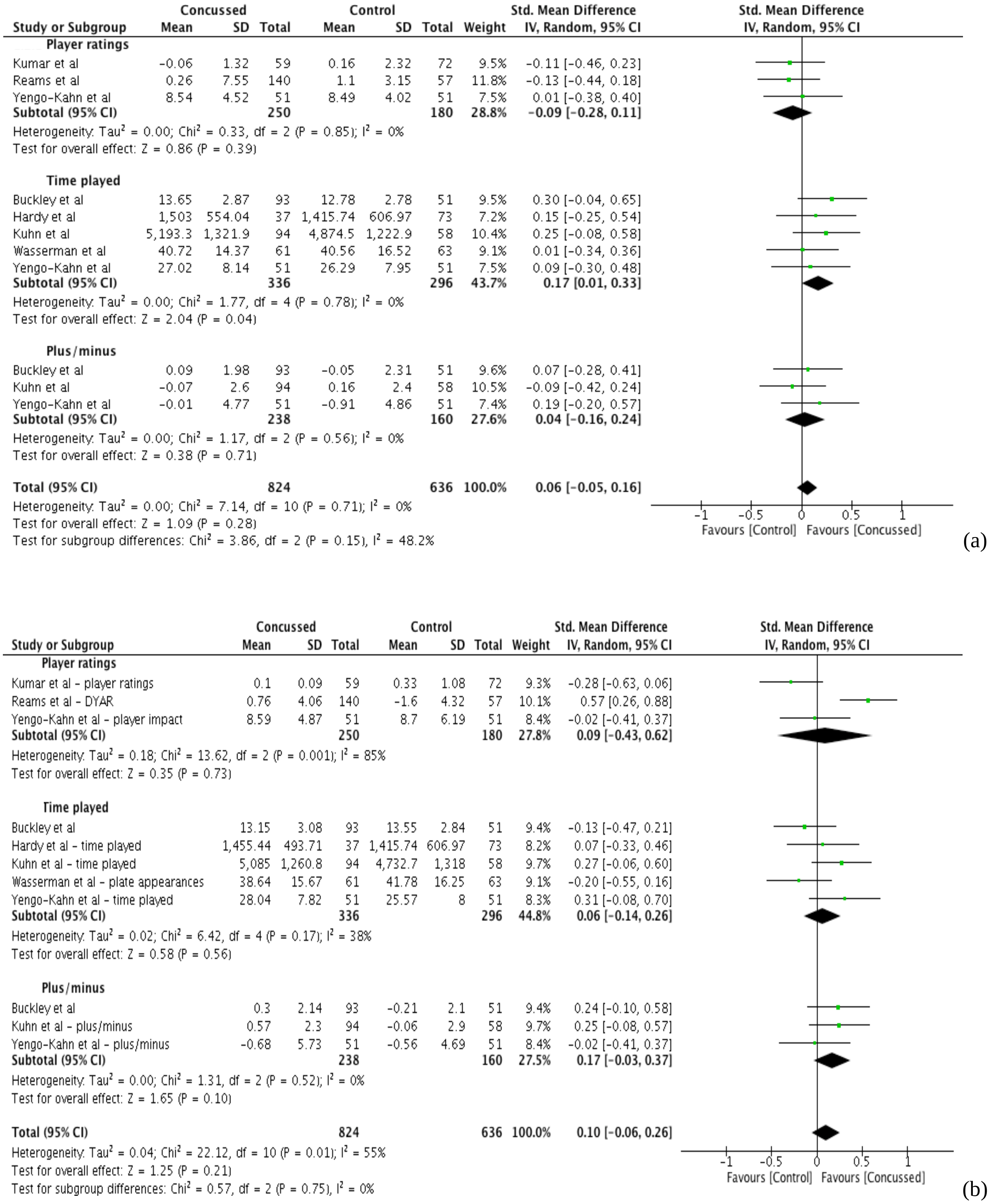


Figure 6: Player evaluation measures between groups pre (a) and post (b) concussion

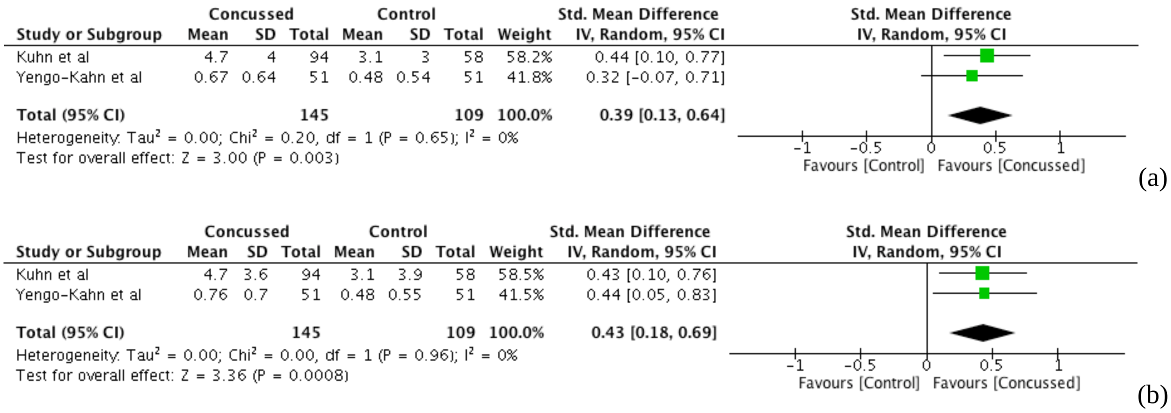


Figure 7: Blocks against player. Pre (a), post (b)

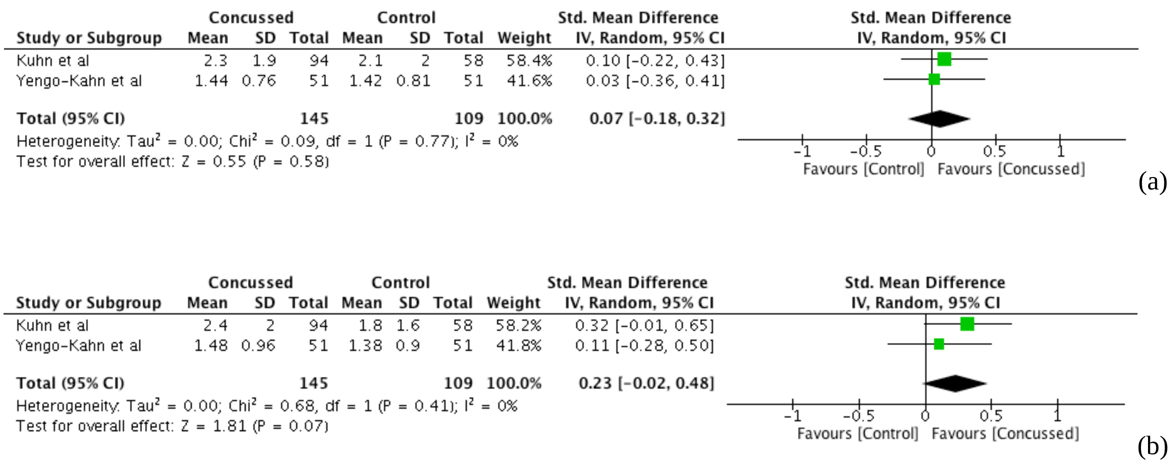


Figure 8: Turnovers against player. Pre (a), post (b)

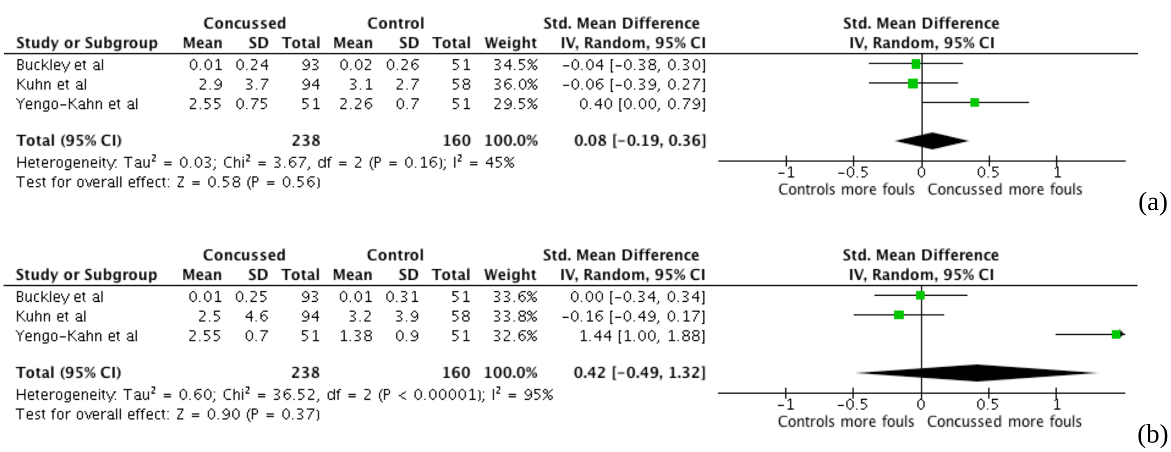


Figure 9: Fouls against player. Pre (a), post (b)

4.1. Within-groups Analysis

Analysis of within-player pre- versus post-concussion (Figures 2 – 4) showed no change in athlete performance, thereby not supporting our first hypothesis. The studies analysed presented common box score statistics specific to their sport, where there are typically more offence-related statistics compared with defense-related statistics, while only three studies reported an overall player rating metric (Kumar et al., 2014; Yengo-Kahn et al., 2016; Zuckerman et al., 2018). These findings collectively indicate that returning to competition following concussion does not have an impact on specific player statistics. However, inclusion of a wider spread of metrics that include both offensive and defensive box score statistics, in addition to an overall player rating metric, would be beneficial to gaining a greater insight into how concussion may or may not affect subsequent in-game performance. Additionally, there is the potential that upon return to play athletes may play reduced game time compared to their pre-injury state. For this reason, applying a time-normalised approach similar to Buckley et al. (2019), while also reporting over various time windows (e.g., +5 games, +10 games, full season), may assist with more meaningful comparisons pre-post concussion and within and between players and sports. It should also be noted that the included studies are relatively recent. Significant increases in concussion awareness, as well as changes in policies and improvement in concussion management procedures in recent years (Gunasekaran, Hodge, Pearce, King, & Fraser, 2019; McCrory et al., 2017) subsequently affect the return to play protocols for athletes and may explain why athlete performance was not compromised as was hypothesised. Indeed, a recent editorial has argued that risk of further concussion is not increased if athletes are managed effectively (Shrier et al., 2019). However, given that studies suggest an increased risk in musculoskeletal injuries following concussion (Brooks et al., 2016; Herman et al., 2017; McPherson et al., 2020; Nordström et al., 2014), future research that include not only sport-specific performance metrics, but also physical metrics (e.g., sprint speed, total distance covered, movement coordination etc.) are required to confirm if athletes who recover from a concussion have reduced in-game performance and physical activity demands capacities.

4.2. Between-groups Comparison

Our second hypothesis for between-group analyses was partly supported with data showing significant differences in *some* variables (e.g., *scoring/ contribution to scoring* and *blocks*) post-concussion. However, an unexpected finding was the significant differences found in pre-concussion data where the concussed group were worse than the control group for goals scored, time played, and blocks against that player. We are unable to explain why differences were found in performance *prior* to a concussion diagnosis, given that all but one study did not show pre-injury differences between groups. Reams et al. (2017), whose study did detect pre-concussion differences between groups, posited that differences in athletic performance before concussion may reflect undetected issues, such as fatigue, or non-disclosure of a concussion from the players themselves before diagnostic confirmation from the team doctor (Brown, Elsass, Miller, Reed, & Reneker, 2015; Pearce, Young, Parrington, & Aimers, 2017). However, it is more likely that our finding of significant differences between groups prior to concussion injury reflects increased sample size power. Further, differences would also reflect limitations of quasi-experimental and observational research design, particularly in applied settings such as in-competition match play. While true experimental pretest-posttest randomised-control designs would be advantageous, these research designs in professional sport are not logically feasible or indeed ethical. Therefore, despite this limitation, it is important to not diminish their contribution to our understanding of concussion in sport. Moreover, the included studies in this systematic review were of moderate-to-good quality. Consequently, we assert that despite limitations in pre-concussion data showing differences between groups, the data reported has value to applied sports science practice.

Further limitations of this study include disparities between team sports differing in characteristics. For example, baseball analyses focused on pitcher versus batter compared to invasion team sports where all players are involved in game play (Yengo-Kahn et al., 2016). Also, this systematic review and meta-analysis only provided data in males, and previous research has shown women have a higher incidence of concussion and a longer recovery time (Agel & Harvey, 2010; Colvin et al., 2009; Howell, Stracciolini, Geminiani, & Meehan III, 2017). Therefore, research that observes any performance changes in female team sport athletes is also required and may differ in presentation of symptoms and outcomes to male athletes. Finally, limitations of these team sports studies confined at the elite level suggest caution in generalising these findings to athletic performance across all sports, including individual sports (specifically combative sports such as martial arts and boxing), and to non-elite levels of participation. Variation in performance metrics can also be considerable from game to game, due to external contextual factors such as opposition strength, travel, time in season, and game outcome (Kempton, Sullivan, Bilsborough, Cordy, & Coutts, 2015; Liu, Gómez, Gonçalves, & Sampaio, 2016). This variation can also make the observation of any concussion-related changes in performance metrics more difficult to observe and should be considered within future work in this area.

5. Conclusion

Understanding the effects of concussion on athletic performance should be as important as understanding the medical effects. While previous research has focused on clinical outcomes that can affect athletes, such as neurological functions, cognition, motor control (e.g., balance), behaviour (e.g., irritability) and sleep/wake disturbances (McCrory et al., 2017) this is the first review to investigate athletic performance. Despite anecdotal concerns from high performance staff members and published studies suggesting concussion-affected performance (Hardy et al., 2017; Wasserman et al., 2015), the pooled data in our meta-analysis does not indicate that concussion affects the on-field performance of elite team sport athletes following return to play. While study methods were determined to be moderate to good in quality (Downs & Black, 1998) the limitation of retrospective designs and disparity in metrics are likely to have contributed to our findings. Prospective studies that report consistent time-normalised metrics, and are conducted in a greater spread of sports and across both sexes will improve the identification of any subtle changes in athletic performance following concussion. For sports science and high performance staff who are accountable for the preparation athlete optimal performance, any effect of concussion on performance will be of importance in athlete preparation and team success, given a small percentage change in performance may be the difference between winning and losing.

Conflict of Interest

The authors declare no conflict of interests.

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Collision monitoring in elite male rugby union using a new instrumented mouth-guard

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ABSTRACT

An instrumented mouth-guard and data analytics platform (PROTECHT) was used to compare collision metrics derived from linear and rotational accelerations of elite rugby union players according to position (forwards and backs), match role (starters and non-starters), match halves (first- and second-half) and six contact types. Analyses were performed at the level of individual collisions and across whole-matches. Fifteen male players from one elite-level rugby union team wore instrumented mouth-guards during 10 matches. Collision metrics were analysed using the PROTECHT system. At the level of individual contacts, linear ($P = 0.034$) and rotational accelerations ($P = 0.049$) were larger in the second-half of matches. Rotational accelerations were highest for ball-carries ($P < 0.05$) compared to aerial challenges and rucks. Analysis of matches demonstrated no differences ($P > 0.05$) between backs and forwards, across all variables, while non-starters had higher mean rotational intensity ($P = 0.006$) and moderate-intensity collisions/min ($P = 0.011$; $d = 0.69$) compared to starters. Linear load/min ($P = 0.041$) and moderate collision counts/min ($P = 0.031$) were also higher in the second-half when comparing all match performances but there were no differences ($P > 0.05$) among those playing both halves. The intensity of collisions increased in the second-half of matches and is likely explained by replacement players. This information can be used to support the utilisation of replacement players. The lower magnitude of head accelerations compared to previous studies requires further research to establish the accuracy of head impact thresholds in rugby union.

1. Introduction

Rugby union is an intermittent team sport, with frequent bouts of static and dynamic collisions (i.e., tackles, contested carries, rucks, mauls), combined with movements of varying intensity (Delaney et al., 2017). While the movement demands of rugby union have been well-characterised (Lindsay et al., 2015; Cunningham et al., 2016; Roe et al., 2016; Tee et al., 2016; Delaney et al., 2017; Reardon et al., 2017; Read et al., 2018), objectively monitoring the frequency, magnitude and type of collisions between players has been historically problematic. This is unfortunate, since physical collisions, by definition, mandate external mechanical loading, leading to tissue trauma, post-match muscle soreness and impaired muscle function among rugby players (Smart et al., 2008; Twist et al., 2012). Furthermore, the majority of injuries sustained in the rugby codes are related to collisions (Fuller et al., 2008; Quarrie & Hopkins, 2008) and the capacity to successfully execute collision-based actions in matches can improve match outcome (Woods et al., 2017; Schoeman & Schall, 2019), and the probability of being selected (Waldron et al., 2014a).

Collisions in the rugby codes have been most commonly identified via description of match video footage (Twist et al., 2012; Waldron et al., 2014a; 2014b; Hendricks et al., 2014; Schoeman & Schall, 2019). These approaches have identified that between 0.3 and 1.1 collisions occur per minute of match-play during contact team sports (Gray et al., 2018). While this

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approach can be considered as a gold-standard for recording collision frequencies and gathering other contextual data, such as the collision type, it does not quantify collision intensity, nor does it provide real-time data and can be labour-intensive for researchers and rugby practitioners (Naughton et al., 2020). To address these limitations, automated tackle and collision detection algorithms have been developed based on signals derived from inertial measurement systems (accelerometers, gyroscopes and magnetometers), which are integrated into Global Positioning System (GPS) devices and worn in an elasticated vest between the scapula of players during training and matches (Kelly et al., 2012; Hulin et al., 2017; Chambers et al., 2019). The intention of these approaches has been to quantify both the frequency and intensity of collision events. However, the materials used to mount and house the inertial measurement devices on players lack the necessary integrity and can lead to signal artefact (McLean et al., 2018). Subsequently, the resulting signal received using this form of micro-technology may be greatly influenced by external noise, thus affecting the reliability of raw accelerations (Waldron et al., 2011), leading to erroneous collision recordings (Reardon et al., 2017).

To overcome the limitations of previous approaches, protective mouth-guards, worn by players in matches, can be instrumented with inertial measurement devices (King et al., 2015). This type of technology can be used to determine raw accelerations (via accelerometers) and angular velocities (via gyroscopes) experienced at the head, with six degrees of freedom. Coupling the sensor to movement of the skull is crucial for accurate detection of linear accelerations and rotational velocities (Wu et al., 2016), thus overcoming errors caused by non-adherence to skin or clothing. While this approach has been more recently adopted to detect head-related impacts in amateur rugby union (King et al., 2015), the same technology has potential to be used to detect whole-body collision events in rugby. The PROTECHT system (https://swa.one/, United Kingdom) is a new analytics platform, which embeds inertial sensors into custom-fit mouth-guards, with potential to provide real-time linear and rotational acceleration data to players and coaches. Therefore, we used the PROTECHT system to monitor the collision frequency and intensity of elite rugby union players, across 10 competitive fixtures. Given the reported collision differences between positional groups (Grainger et al., 2018; Macleod et al., 2018; Yamamoto et al., 2020), contact types (Macleod et al., 2018), and fatigue-induced changes in tackling frequency across match periods (Tee et al., 2016), we also compared collision characteristics between: 1) forwards and backs, 2) starter and non-starters, 3) first and second-halves and 4) six distinct contact types. Therefore, the overall aim was to evaluate metrics derived from linear and rotational accelerations, recorded via the PROTECHT system, at the level of individual collisions and across whole matches according to these factors.

2. Methods

2.1. Subjects

Fifteen elite male rugby union players (mean ± SD: age = 26 ± 4 years; body mass = 104.3 ± 12.4 kg; stature = 1.86 ± 0.05 m) provided written, informed consent to take part in this study. Institutional ethical approval was provided for this study, which was conducted in accordance with the 2013 Helsinki Declaration.

2.2. Design

An observational cohort study was conducted on fifteen elite rugby union players, across 10 competitive matches in the 2019-2020 season. Players wore custom-fitted instrumented mouth-guards during matches (PROTECHT system), from which collision metrics were recorded and analysed post-hoc. Data were characterised at two levels; per contact (n = 978) and per match performance (n = 43). Comparisons were made between 1) positions (forwards (n = 9) vs. backs (n = 6)), 2) match halves (first *vs.* second), 3) starters vs. non-starters and 4) six contact types. The contact types were: aerial collisions, rucks, tackles, carries, scrum/mauls and unavoidable collisions (see Schoeman & Schall 2019, for definitions). Aerial collisions defined as a collision that occurred from a player competing to catch a ball from a kick which resulted in an impact meeting the system's collision criteria. Unavoidable impacts were defined as a collision that a player received undertaking a number of activities not defined or measured in OPTA. These could be a player hitting the floor after a tackle, a player being bumped by another player in defence or attack or a kick chase, which resulted in an impact meeting the system's collision criteria. The selected comparisons and sample sizes varied according to the level of analysis (i.e., per contact or match performance). An additional comparison of match halves was performed among those performing in both halves of matches (n = 22).

2.3. Procedure

The PROTECHT system includes an iMG containing a tri-axial accelerometer (H3LIS331DL, STMicroelectronics, Genova, Switzerland) and a tri-axial gyroscope (LSM9DS1, STMicroelectronics, Genova, Switzerland). The former was sampled at 1 kHz (± 200 g, 16-bit resolution) and the latter at 952 Hz (± 35 rad/s, 16-bit resolution). Each recorded collision event was video-verified using OPTAPRO (OPTAPRO, www.optaprorugby.com, London, United Kingdom) to determine contact type, in addition to assessing the sensitivity (91%), specificity (95.7%) and accuracy (95.1%) of the PROTECHT system in identifying all collision events in rugby union, which is consistent with data from other activities (Mcnamara et al., 2015; Macleod et al., 2018). The device has been technically validated and closely compares (95% Limits of Agreement: peak linear acceleration = -2.6 ± 9.2 g, peak rotational acceleration = 230 ± 492 rad/s/s) to criterion measures (unpublished data), with intra-class correlation coefficient values of 0.91 for peak linear acceleration and 0.95 for peak rotational acceleration.

2.4. Measurement

Collisions recorded by the PROTECHT system were identified as meeting set criteria, as follows: 1) the mouth-guard was in players' mouths, as determined by an infrared sensor embedded within the mouth-guard and 2) any linear acceleration value exceeding 10 g

was transmitted. If it did not exceed 10 *g* the data were removed, except from those that were video-verified. This threshold level was chosen based on a review of previous studies (King et al., 2015). The impacts below the threshold level were considered to negligible and, therefore, eliminated non-impacts events, such as running and jumping (Ng et al., 2006). If it did not exceed 10 *g* the data were removed, except from those that were video-verified. This threshold level was chosen based on a review of previous studies (King et al., 2015). The impacts below the threshold level were considered to negligible and, therefore, eliminated non-impacts events, such as running and jumping (Ng et al., 2006).

For each collision, the inertial sensors collected 104 ms of data, for linear acceleration and rotational velocity. Rotational accelerations were derived from the rotational velocity time-series using a five-point stencil. Spectral analysis on the linear acceleration-time series data, which identified no obvious high frequency (i.e., > 200 Hz) components in the signal. Therefore, the data were not filtered. The measured rotational velocity was filtered on-chip via an anti-aliasing filter at 105 Hz and a low-pass filter with a cut-off of 100 Hz. Peak values reported were defined as the maximum numerical value of the vector-norm of the respective time-series data. Collision intensity was categorized based on the average z-score for peak linear and rotational value from the collision event. Intensity bandings were determined through standard deviation values: weak ⩽ -1, Light -1-0, moderate 0-1, strong 1-2 and very strong >2 SD. The remaining variables are described in Table 1.

2.5. Statistical analysis

Analyses were conducted at two levels; model 1) all individual collisions and model 2) total match-collision profiles (model 2). In model 1, after log-transformation of data, a fully factorial linear mixed model was used to identify differences in individual collision metrics (across 978 separate collision events) between positional groups (backs vs. forwards), halves of the match (first or second), match role (starters vs. non-starters) and collision type (aerial, tackle, carry, scrum, maul, unavoidable collisions). Each of the above variables were treated as fixed factors and each individual player was included as a random effect. In model 2, a linear mixed model was also used to assess differences between positions, match halves and match roles, across 20 separate collision metrics. Differences between halves of the match were assessed on all match files and on players only completing both halves of the whole match. The same organization of fixed and random factors was used. Fixed effects and interactions were followed up with Bonferroni *post-hoc* tests to identify pairwise differences. Statistical significance was recognised when $P < 0.05$. Cohen's *d* effect sizes were calculated, with thresholds set as: ≤ 0.2 small; ≤ 0.6 moderate; ≤ 1.2 large; ≥ 2.0 very large (Hopkins et al., 2009). Statistical analyses were performed using SPSS version 24 (IBM SPSS Statistics Inc, Armonk, USA).

Table 1: Collision variable and definition

Variable	**Definition**
Count (*n*)	Number of all collision events recorded for the player in a match
Mean linear intensity (*g*)	The mean peak linear acceleration value attained for all collisions in a match
Mean rotational intensity (rad/s/s)	The mean peak rotational acceleration value attained for all collisions in a match
Peak linear intensity (*g*)	The highest linear acceleration value attained from an collision in a match
Peak rotational intensity (rad/s/s)	The highest rotational acceleration value attained from an collision in a match
Linear load (AU)	Accumulated sum of peak linear acceleration values for all collisions in a match
Rotational load (AU)	Accumulated sum of peak rotational acceleration values for all collisions in a match
Weak count (*n*)	Number of z-score derived weak collisions an athlete receives for a match
Light count (*n*)	Number of z-score derived light collisions an athlete receives for a match
Moderate count (*n*)	Number of z-score derived moderate collisions an athlete receives for a match
Strong count (*n*)	Number of z-score derived strong collisions an athlete receives for a match
Very strong count (*n*)	Number of z-score derived very strong collisions an athlete receives for a match

Note: all variables are also expressed per minute of match time (n/min).

3. Results

3.1. Collision characteristics by contact

Both linear (P = 0.515; d = 0.12) and rotational accelerations (P = 0.216; d = 0.11) during each collision were not different between backs and forwards (Figure 1A). Similarly, linear (P = 0.101; d = 0.23) and rotational (P = 0.078; d = 0.20) accelerations were not different between starters and non-starters (Figure 1C). However, linear (P = 0.034; d = 0.25) and rotational accelerations (P = 0.049; d = 0.21) were larger in the second-half of matches (Figure 1B). Lastly, there was a main effect of collision type for both linear (P = 0.045) and rotational accelerations (P = 0.018), with *post-hoc* tests demonstrating differences between carries and aerial challenges (P = 0.008; d = 0.59) or carries and rucks (P = 0.045; d = 0.35) for rotational accelerations only (Figure 2A).

3.2. Collision characteristics by match

Analysis of match profiles demonstrated no differences ($P > 0.05$) between backs and forwards, across all variables (Table 2). However, non-starters had higher mean rotational intensity (P = 0.006; d = 0.75) and moderate-intensity collisions/min (P = 0.011; d = 0.69), while total collision counts (P = 0.011; d = 0.93) and total linear load was higher in the starters (P = 0.019; d = 0.85) (Table 2). Linear load/min (P = 0.041; d = 0.42) and moderate collision counts/min (P = 0.031; d = 0.52) were higher in the second-half when comparing all match performances but there were no differences ($P > 0.05$) among those playing both halves of the match (Table 3).

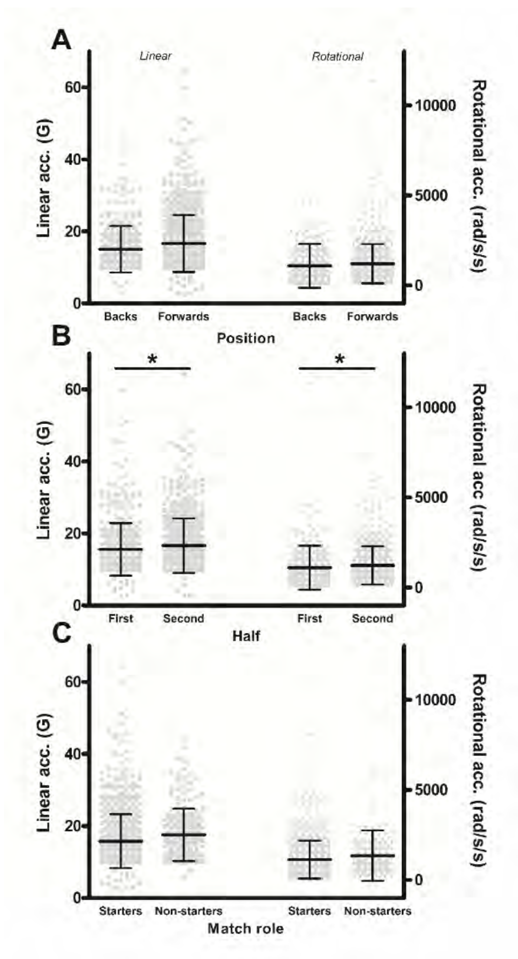

Figure 1: Linear (left) and rotational (right) accelerations measured via the PROTECHT system during elite rugby matches and comparisons of position (A; forwards vs. backs), match halves (B; first vs. second) and match role (C; starters vs. non-starters). * = difference ($P < 0.05$) between first- and second-half.

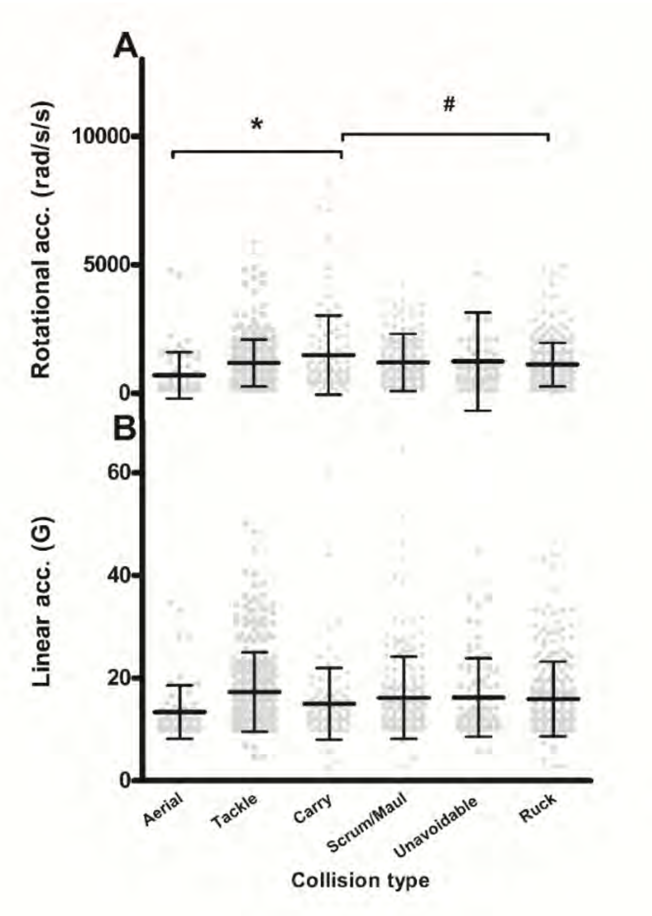

Figure 2: Rotational (A) and linear (B) accelerations measured via the PROTECHT system during elite rugby matches by collision type. * = difference ($P < 0.05$) between carry and aerial collisions; # = difference ($P < 0.05$) between carry and unavoidable collisions. Acc. = acceleration.

Table 2: Collision characteristics (mean ± SD) of backs *vs.* forwards and starters *vs.* non-starters

	Backs *vs.* Forwards		**Starters *vs.* Non-starters**	
	***n* = 13**	***n* = 30**	***n* = 27**	***n* = 16**
Count (*n*)	25.1 ± 25.5^{S}	21.5 ± 17.2	29.5 ± 22.3^{L}*	12.3 ± 8.2
Count/min (*n*/min)	0.34 ± 0.33^{M}	0.51 ± 0.34	0.42 ± 0.29^{M}	0.51 ± 0.41
Mean linear intensity (*g*)	16.1 ± 3.1^{M}	17.1 ± 2.7	16.3 ± 3.1^{M}	17.5 ± 2.2
Mean rotational intensity (rad/s/s)	1308.3 ± 540.1^{M}	1186.9 ± 393.3	1106.2 ± 296.4^{L}*	1421.7 ± 568.1
Peak linear intensity (*g*)	30.6 ± 9.3^{M}	34.2 ± 12.1	34.5 ± 12.5^{M}	30.8 ± 9.2
Peak rotational intensity (rad/s/s)	4113.9 ± 3757.4^{S}	3564.4 ± 2427.1	3742.9 ± 2329.2^{S}	3708.9 ± 3669.8
Linear load (AU)	376.9 ± 359.9^{S}	358.3 ± 271.1	451.9 ± 327.8^{L}*	215.6 ± 149.3
Rotational load (AU)	26749.1 ± 22666.4^{S}	25816.3 ± 22705.4	31642.6 ± 24766.5^{M}	16743.1 ± 14013.1
Linear load/min (AU/min)	5.08 ± 4.8^{L}	8.6 ± 6.1	6.6 ± 4.4^{M}	9.1 ± 7.6
Rotational load/min (AU/min)	361.6 ± 298.1^{M}	604.6 ± 464.4	458.6 ± 326.3^{M}	653.5 ± 559.7
Weak count (*n*)	0.23 ± 0.43^{S}	0.23 ± 0.67	0.29 ± 0.72^{M}	0.12 ± 0.34
Light count (*n*)	15.2 ± 19.2^{M}	12.1 ± 11.7	17.5 ± 16.1^{L}*	5.5 ± 5.1
Moderate count (*n*)	7.6 ± 5.6^{S}	6.8 ± 5.3	8.2 ± 5.9^{M}	5.1 ± 3.7
Strong count (*n*)	1.7 ± 1.9^{S}	2.1 ± 2.1	2.2 ± 2.2^{M}	1.4 ± 1.6
Very strong count (*n*)	0.23 ± 0.59^{M}	0.76 ± 1.3	0.81 ± 1.3^{M}	0.25 ± 0.44
Weak count/min (*n*/min)	0.01 ± 0.01^{S}	0.01 ± 0.01	0.01 ± 0.01^{S}	0.01 ± 0.01
Light count/min (*n*/min)	0.2 ± 0.25^{M}	0.27 ± 0.22	0.25 ± 0.21^{S}	0.25 ± 0.26
Moderate count/min (*n*/min)	0.11 ± 0.07^{M}	0.17 ± 0.12	0.12 ± 0.07^{L}*	0.19 ± 0.14
Strong count/min (*n*/min)	0.03 ± 0.02^{M}	0.05 ± 0.06	0.03 ± 0.03^{M}	0.05 ± 0.07
Very strong count/min (*n*/min)	0.004 ± 0.009^{M}	0.02 ± 0.03	0.01 ± 0.02^{S}	0.01 ± 0.02

Note: * = sig. different ($P < 0.05$) to comparison group. Cohens *d*: S = small, M = moderate, L = large.

Table 3: Collision characteristics (mean ± SD) of the first and second-half of matches

	First-half vs. Second-half *All matches*		**First-half *vs.* Second-half** *Whole-matches*	
	n = 28	***n = 37***	***n = 22***	***n = 22***
Count (*n*)	16.1 ± 11.5^{S}	14.1 ± 11.8	16.1 ± 11.7^{S}	16.2 ± 13.4
Count/min (*n*/min)	0.41 ± 0.28^{M}	0.51 ± 0.41	0.41 ± 0.28^{M}	0.51 ± 0.38
Mean linear intensity (*g*)	15.8 ± 3.1^{M}	16.8 ± 4.1	15.6 ± 3.1^{S}	16.2 ± 5.1
Mean rotational intensity (rad/s/s)	1184.8 ± 628.7^{S}	1253.4 ± 442.3	1233.6 ± 682.3^{S}	1245.6 ± 470.9
Peak linear intensity (*g*)	29.1 ± 10.8^{S}	31.1 ± 11.7	28.9 ± 11.1^{M}	31.9 ± 12.9
Peak rotational intensity (rad/s/s)	3548.2 ± 3297.3^{S}	3331.1 ± 2507.2	3740.6 ± 3480.9^{S}	3532.2 ± 1835.4
Linear load (AU)	252.3 ± 177.1^{S}	231.9 ± 183.2	252.6 ± 183.2^{S}	260.4 ± 204.3
Rotational load (AU)	17600.1 ± 12733.2^{S}	17011.2 ± 14033.4	18082.2 ± 13392.2^{S}	20032.1 ± 15833.5
Linear load/min (AU/min)	6.3 ± 4.2^{M*}	8.7 ± 6.8	6.4 ± 4.4^{M}	8.3 ± 6.1
Rotational load/min (AU/min)	466.5 ± 340.2^{M}	610.6 ± 486.8	489.3 ± 361.6^{M}	613.1 ± 415.3
Weak count (*n*)	0.25 ± 0.64^{M}	0.08 ± 0.27	0.31 ± 0.71^{M}	0.09 ± 0.29
Light count (*n*)	9.7 ± 9.2^{M}	7.7 ± 8.2	9.5 ± 8.8^{S}	9.4 ± 9.4
Moderate count (*n*)	4.6 ± 2.9^{S}	4.6 ± 3.6	4.7 ± 3.1^{S}	4.8 ± 4.1
Strong count (*n*)	1.1 ± 1.4^{M}	1.4 ± 1.3	1.2 ± 1.4^{M}	1.6 ± 1.4
Very strong count (*n*)	0.5 ± 1.2^{M}	0.3 ± 0.6	0.41 ± 1.01^{S}	0.36 ± 0.78
Weak count/min (*n*/min)	0.01 ± 0.01^{S}	0.01 ± 0.01	0.01 ± 0.02^{S}	0.01 ± 0.02
Light count/min (*n*/min)	0.24 ± 0.22^{S}	0.27 ± 0.27	0.23 ± 0.22^{S}	0.27 ± 0.27
Moderate count/min (*n*/min)	0.11 ± 0.07^{M*}	0.17 ± 0.14	0.12 ± 0.07^{M}	0.15 ± 0.13
Strong count/min (*n*/min)	0.03 ± 0.04^{M}	0.05 ± 0.06	0.03 ± 0.05^{M}	0.05 ± 0.04
Very strong count/min (*n*/min)	0.01 ± 0.03^{S}	0.01 ± 0.02	0.01 ± 0.02^{S}	0.01 ± 0.02

Note: * = sig. different ($P < 0.05$) to comparison group. Cohens *d*: S = small, M = moderate, L = large. 'Whole- matches are those where players completed the entire game on the field, while 'All' matches encompass those where players were substituted on or off the field.

4. Discussion

We investigated, for the first time, the characteristics of individual and total match collisions, using the validated PROTECHT system. The frequency of collisions recorded for each player/match (~30 collisions or 0.42/min) is in accordance with that reported across rugby codes using video, GPS-housed inertial sensors (Naughton et al., 2020). However, the mean intensity (linear ~16-17 vs. ~22 *g*; rotational ~1,100 - 1,400 *vs*. ~3,600 - 4,400 rad/s/s) and frequency of collisions (~30 vs. ~50-95) were markedly smaller than reported from other instrumented mouth-guards used in amateur rugby union (King et al., 2015). A detailed discussion of these discrepancies is beyond the remit of the current study but it appears to relate to hardware and signal processing differences between devices, resulting in the PROTECHT system reporting systematically lower frequency and intensity of collisions compared to others (X2Biosystems Inc). The ‘bulky fit’ and technical error of the previous instrumented mouth-guard was noted by the authors (King et al., 2015), which may have been improved by the custom-fit of the PROTECHT system mouth-guards. This raises some cause for concern, given that data from the older system (X2Biosystems Inc.) has been used to determine concussion risk thresholds in rugby union (King et al., 2015) and could be overestimating head collision frequency and intensity. Further work is required to compare the performance of the two systems in order to validate the concussion risk thresholds.

The initial analysis of individual collisions, which removes the match context, showed that both linear and rotational accelerations did not differentiate positional groups or starters/non-starters, but were larger in the second-half of matches. Carries had the descriptively largest collision intensities, with aerial challenges and unavoidable collisions the smallest in comparison. Analysis of match-collision profiles showed a similar pattern of results, with first-to-second half differences in linear load and moderate collisions (expressed relative to playing time) only apparent when all match files were considered, rather than those playing both halves. Analysis of playing role showed that non-starters had higher mean rotational intensities and relative moderate collisions compared to starters, thus explaining the increase in collision metrics between match halves.

We anticipated that there would be a decline in collision metrics between the first- and second-half of matches. However, both the individual and match-level analyses performed questioned this, demonstrating that most variables were unchanged between halves of the match, with some collision characteristics actually increasing. Indeed, our refined analysis of players performing in both halves of matches also showed no differences in any measured variable. This indicates that the primary reason for second-half increases is the introduction of replacement players (non-starters) and that the effect of fatigue (Tee et al., 2016) does not appear to manifest in collision measurements of this type. The reasons for this are not entirely clear but the different technological approaches between this and previous studies might be partly attributable. For example, collision detection algorithms based on data from inertial sensors housed within GPS devices have been recently criticised, owing to their poor validity and insufficient sensitivity for measuring collision frequency and/or intensity (Chambers et al., 2019; Naughton et al., 2020). This has been suggested to partly relate to the placement and mounting surfaces of the device, which is subject to movement artifact. It is feasible that erroneous collision recordings (i.e., false positives/negatives) lead to misinterpretation of between-half changes, particularly when collisions are low-intensity or short duration (Hulin et al., 2017). This is overcome by the iMG used herein, which couples the movement of the skull and is sufficiently sensitive to stratify on-field collisions into intensity bands. Furthermore, given the importance of intensity in determining ‘load’ (intensity x volume or frequency), the current system offers greater understanding of collision characteristics. This was supported by the variables that increased in the second-half or were higher among starters (linear load or moderate collisions/min), which rely upon accurate quantification of collision magnitude (intensity). For example, linear load summates all linear collisions performed, and when expressed relative to playing time (linear load/min), provides an indication of the collision ‘density’ and could be adopted by rugby coaches when using the PROTECHT system.

Irrespective of the analyses performed (i.e., individual contacts or match files), we did not find any positional differences across the 10 matches (involving 15 players). This was somewhat surprising, given the consistency of reported higher collision frequencies among forwards compared to backs using other technologies (Grainger et al., 2018; Macleod et al., 2018; Yamamoto et al., 2020). The preliminary nature of the current analysis could partly explain these results, as the dispersion of data was large relative to the mean values, which might preclude the identification of significant differences, despite effect sizes ranging from small to large (Table 3). Furthermore, the use of only one team limits the generalisability of the results to the wider elite rugby population and precluded further positional categorisation. Nevertheless, previous analyses of similar samples to the current study have identified differences between forwards and backs in collision metrics (Reardon et al., 2017), which raises the possibility that collisions measured at the head using mouth-guard technology are more homogenous across positions than previously considered. In support of this, differences in the intensity of head collisions (using alternative mouth-guard technology) between forwards and backs were not as clearly identifiable (King et al., 2015). Collisions in matches can often be contests between players from any positional group, thus, it is feasible all have equal probability of being co-involved in high-impact collisions. It is also possible that the alternative methods (GPS-housed or video) used for detecting collisions include contacts that are unrecognised at the head (i.e., contact anatomically inferior to the head) or are filtered from the PROTECHT system’s recordings (i.e., < 10 *g*). This will alter the identification of collisions and consequent interpretation of group differences. Therefore, our preliminary data suggest that players of all positions have equal probability of being involved in collisions of varying intensity when measured using mouth-guard technology.

Analysis of the six collision types demonstrated that aerial balls and unavoidable collisions had less rotational intensity compared to carries. Ball-carrying is an important rugby-specific skill that can positively affect the outcome of matches (Schoeman

& Schall, 2019) or team selection (Waldron et al., 2014a) Carrying the ball into opposition contact with high-intensity increases the force and momentum of the player at the point of collision, which relates to successful collision outcomes (Hendricks et al., 2014; Waldron et al., 2014b). This also makes ball-carriers a natural target for impactful challenges from the opposition, who also contribute an external application of force to the ball-carriers measured impact (Hendricks et al., 2014). Carrying the ball into contact typically involves three phases; the approach (or 'entry'), an initial collision and a final static or quasi-static exertion. The nature of each phase (and therefore the entire collision) is unpredictable, which leads to a multitude of outcomes and resultant forces. For example, the energetic contribution of a player tackling the ball-carrier from a wide angle, while rapidly accelerating and targeting the upper-body, is likely to elicit a large rotational acceleration on the ball-carrier. Indeed, this type of contact is fairly common in rugby and could explain the higher rotational demands of ball-carriers (Figure 2A). This is noteworthy, since rotational head accelerations have been associated with diffuse head injury (Rowson et al., 2016). Although the exact timing of the rotational acceleration was not determined in the current study, exposure to high rotational forces, particularly during the final stationary phase of a collision could pose a risk to player safety. In this scenario, the player's capacity to re-direct energy of the contact is constrained, and the common involvement of second tacklers or secondary impacts from support players may exacerbate these risks. Of further note, the analysis of non-starters demonstrated higher mean rotational intensity and more than a three-fold reduction in light contacts in favour of higher moderate contacts/min (Table 3). Thus, replacement players choose to exert their influence on the match by adopting strategies that preferentially increased the magnitude of rotational accelerations. Further research is required to understand how this is achieved.

This study provides preliminary evidence that the PROTECHT system could be used by coaches to assess the 'impact' of their replacement players in the second-half of matches. Indeed, if the tactical intention is for the non-starters to increase the collision demands of the match when being introduced, then our data confirm that this is often achieved. The ability to determine this is currently not afforded by GPS-housed inertial sensors. Our data also has implications for the performance of the ball-carrier, who will need to develop the skill and physical ability to maintain ball possession, while receiving the highest rotational forces in a short period of time. The lowest rotational collision accelerations found during aerial balls probably relates to the intentional withdrawal of tackling players in accordance with rugby union laws, thus providing some evidence of its efficacy in reducing collision loads of air-borne players.

In conclusion, using the PROTECHT system, we have demonstrated that the intensity of collisions in elite rugby union matches tends to increase in the second-half of matches and is captured by linear load/min and moderate counts/min. Given that players completing both halves of matches do not change their collision metrics, the increased collision intensity was likely to be explained by the introduction of replacement players to the match. Players carrying the ball showed the largest rotational collision intensities, with aerial challenges and unavoidable collisions the smallest in comparison. Forwards and backs were not different across any collision metric. This information can be used to support rugby coaches' decisions to utilise replacement players in the second-half, if their intention is to increase the collision intensity. Our data also demonstrates how the ball-carrying players experience the largest collisions measured at the head and that this is more likely to occur in the second-half when fatigue typically ensues. Specific skills training and physical conditioning can be adopted to account for this occurrence and does not appear to require position-specific focus. The rather large differences between other mouth-guard systems raises some concerns and further work is required to understand the reasons for these disparate findings.

Conflict of Interest

There was no financial support provided for this study; however, a financial relationship exists between Sports and Wellbeing analytics Limited (SWA) and Swansea University. The PROTECHT system has been developed by SWA and authors from both SWA and Swansea University are included in this current paper. The authors from Swansea University had full access to all of the data in this study and take full responsibility for their integrity and analysis. The results of the current study do not constitute endorsement of the product by the authors or the journal.

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Phase specific changes in the countermovement jump occur without change in peak metrics following training

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ABSTRACT

The countermovement jump (CMJ) is routinely used to assess changes in strength-power qualities. Common measures derived from this test include jump height, peak power and peak velocity. However, valuable information on training induced changes in CMJ performance may be missed if phase and subphase variables are not included in the analysis also. The objective of this investigation was to determine whether significant performance changes can occur in the CMJ in the absence of changes in jump height or peak-form metrics. Sixteen recreationally trained males undertook 10-weeks of resistance training consisting of weightlifting, ballistic and plyometric actions with heavy and light loads. The CMJ was performed pre- and post-test with both peak-form metrics and mean phase/subphase metrics analysed. Mean velocity ($p < 0.01$) and mean power ($p < 0.01$) significantly improved following training while peak velocity ($p = 0.18$), peak power ($p = 0.29$), and jump height ($p = 0.24$) did not. Work, countermovement depth, eccentric duration and total movement duration significantly improved too ($p < 0.01$ to 0.03). Practitioners should consider using CMJ variables beyond jump height and instantaneous metrics to more thoroughly diagnose performance changes of the leg extensors following training.

1. Introduction

The countermovement jump (CMJ) is routinely used to assess changes in strength-power qualities in response to training (Cormie, McBride, & McCaulley, 2009; Harrison, James, McGuigan, Jenkins, & Kelly, 2019; McMahon, Suchomel, Lake, & Comfort, 2018). Although a multitude of measures can be derived from this test, arguably the most common are jump height, peak power and peak velocity. Peak measures are the highest value across a single sample and are therefore dictated by the sampling frequency of the instrumentation (e.g., 1000 Hz = 0.001s). CMJ velocity, power and force can also be averaged over phases of interest, like the concentric phase (~0.1 to 0.3s). These mean-form variables provide greater insight into changes throughout the CMJ than isolated measures because they enable researchers and practitioners to consider longer periods of phases of interest rather than a single data point (e.g., 0.001s) (Lake, Mundy, Comfort, & Suchomel, 2018). Furthermore, explosive athletic actions occur over more similar epochs to that of mean-form metrics suggesting that these variables are of greater relevance to sports performance, particularly from a temporal perspective (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002; Tidow, 1990). A focus on peak metrics alone might therefore cause the analyst to miss key underlying performance changes and draw erroneous conclusions about the state of the training process.

While light ballistic and heavy strength training modalities have resulted in considerable increases in peak CMJ measures (e.g., peak velocity), improvements in the equivalent mean variables (e.g., mean velocity) are more modest (Cormie, McGuigan, & Newton, 2010b, 2010c). One possible explanation for this is that previous investigations included only a single exercise modality and narrow loading conditions which consequently limited adaptations throughout the entire range of motion, resulting in attenuated improvements in phase/sub-phase metrics. This is a notable limitation as training plans in a sporting

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setting are typically mixed modality (Ebben, Carroll, & Simenz, 2004; Ebben, Hintz, & Simenz, 2005; Simenz, Dugan, & Ebben, 2005). In other words, they consist of a range of loading conditions and multiple forms of resistance training tasks such as ballistic, plyometric and heavy strength training.

The primary purpose of this investigation was to determine if a mixed modality resistance training intervention would elicit significant changes in CMJ phases and subphases without increases in common peak-form metrics (including jump height).

2. Methods

2.1. Participants and Training Intervention

Sixteen recreationally trained males (age: 25.5 ± 4.2 years; height 1.77 ± 0.08 m; body mass [BM]: 79.4 ± 11.2 kg; 1 repetition maximum squat: 1.60 ± 0.45 kg·kg·BM-1) undertook 10 weeks of resistance training, three days per week, consisting of weightlifting, ballistic and plyometric modalities under a spectrum of loads. Training has been described in detail previously (James et al., 2018) and is presented in Table 1.

2.2. Countermovement Jump Assessment

The CMJ test was performed on a force platform (Bertec Corporation, Columbus, OH, USA, sampling at 2000 Hz) at baseline and post-test using documented procedures (James et al., 2018). All CMJ force-time data were processed in a customisable spreadsheet. Briefly, force-time data were averaged over the first 1s of quiet standing to calculate subject weight. Additionally, the standard deviation of this period was quantified and the jump start threshold was determined by multiplying this by five and either subtracting this from or adding it to the subject's weight (depending on whether the maximum quiet standing force-time value was less or more than weight ± 5 SD). This weight was then subtracted from the force-time data to provide net force, which was then divided by body mass (weight ÷ the acceleration of gravity [a, 9.81 m/s/s]) to yield the acceleration of the centre of mass. A backward search was then performed from the 'jump start' to identify the last force-time intersection matching the weight (calculated on a trial-by-trial basis) and acceleration-time data were integrated from this point using the trapezoid rule to yield the velocity of the centre of mass. Power was then calculated by multiplying force by velocity on a sample-by-sample basis. Peak and mean velocity and power were calculated as the highest instantaneous value from the propulsion phase and as the value averaged over the propulsion phase respectively. Work was calculated by multiplying mean propulsion power by time. The eccentric phase was identified as beginning at the lowest countermovement velocity, ending at the transition from negative to positive velocity (lowest countermovement displacement); this marked the beginning of the propulsion phase, which ended at take-off. Countermovement depth was calculated as the change in centre of mass position from the jump start to the beginning of the propulsion phase, while eccentric duration was calculated as time from the lowest countermovement velocity until the start of the propulsion phase.

Table 1: Training intervention for this investigation. Loading for the weightlifting derivatives was taken from the power clean one-repetition maximum. Jump squat loading was taken from the one-repetition maximum back squat. Both these lifts were reassessed at mid-testing. All participants were familiar with the training and testing procedures. Where a range is given for loading, the lighter load was performed on day 1 and the heavier load on day 3. The depth jump volume progressed from three sets of three in week six to five sets of four in week 10.

Baseline-testing week								
	Day 1 and 3				Day 2			
Training Weeks 1-5	Exercise	Sets	Reps	Loading	Exercise	Sets	Reps	Loading
	Power clean	5	5	70%	Hang power clean	4	5	55%
	Jump squat	5	5	40-50%	Snatch pull	4	5	70%
Mid-testing week								
Training Weeks 6-10	Exercise	Sets	Reps	Loading	Exercise	Sets	Reps	Loading
	Jump squat	5	5	0-30%	Hang power clean	5	4	70%
	Power clean	5	4	85%	Snatch pull	5	4	85%
	Depth jump	3-5	3-4		Plyometric rebound split squat	4	3 each	
Recovery week								
Post-testing								

Table 2: Mean (SD) changes in countermovement jump variables following training. *d* = Cohen's *d* effect size.

	Pre		Post		*P*	*d*
Peak Power (W)	3780	(725)	3883	(564)	0.29	0.16
Mean Power (W)	1853	(369)	2006	(316)	<0.001	0.44
Peak Velocity (m·s^{-1})	2.65	(0.30)	2.72	(0.19)	0.18	0.28
Mean Velocity (m·s^{-1})	1.43	(0.19)	1.53	(0.13)	<0.001	0.58
Work (J)	600.67	(98.32)	644.20	(89.53)	<0.001	0.46
Countermovement Depth (m)	0.47	(0.05)	0.49	(0.04)	0.03	0.59
Eccentric Time (s)	0.31	(0.09)	0.23	(0.04)	<0.001	-1.02
Total Time (s)	1.12	(0.20)	0.98	(0.14)	0.01	-0.76

We then calculated and identified the middle 50% of 'initial flight' and referred to this as 'flight'. The mean (SD) 'flight' phase force was calculated, SD multiplied by 5 and this was added to the mean 'flight' force to identify take-off (first force <mean + 5 SD 'flight' force). Jump height was calculated from take-off velocity (take-off velocity2 ÷ 2a) and total movement duration was calculated as the period between the start and take-off.

2.3. Statistical Approach

Following confirmation of normality a paired samples t-test was used to determine whether there was a significant change in outcome variables following training (SPSS, Version 23.0, IBM Corporation, Somers, New York, USA). Cohen's *d* effect sizes were also calculated (Microsoft Excel 2013, Microsoft Corporation, Washington, USA).

3. Results

Significant increases in mean velocity and mean power were revealed following training in the absence of significant changes in peak velocity, peak power (Figure 1), and jump height. Work, countermovement depth, eccentric duration and total movement duration all changed significantly (Table 2). No change in BM occurred at post-test ($p = 0.35$).

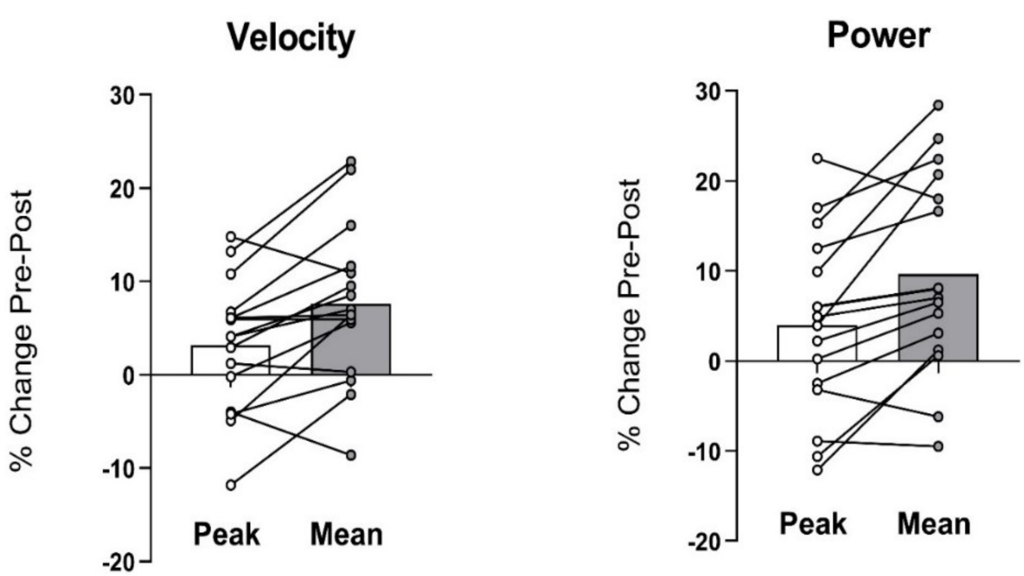

Figure 1: Individual changes in countermovement jump peak and mean velocity in addition to peak and mean power following strength-power training.

4. Discussion

The primary objective of this study was to determine whether changes in CMJ phase/subphase measures would occur in the absence of changes to peak metrics (e.g., peak power, jump height) following an ecologically valid resistance training intervention. These findings revealed statistically significant changes in several CMJ measures despite no alterations in peak velocity, peak power and jump height. These results show is that when analysing CMJ performance in a training environment it is important to consider all relevant variables to properly understand performance changes of the leg extensors. For example, if only peak velocity, peak power and jump height were analysed, as is often the case, an erroneous conclusion would have been drawn from these results because it could have suggested that the intervention did not effectively improve explosive leg muscle function. However, by including variables that enable study of CMJ jump strategy (mean velocity and power, work, and phase and sub-phase durations) we can see that this training strategy had positive and meaningful effect.

The intervention enabled subjects to increase their countermovement depth by an additional 2 cm. This has the potential to increase the stretch shortening cycle stimulus, particularly when combined with the fact that eccentric braking duration decreased significantly (Cormie, McGuigan, & Newton, 2010a). Because body mass remained consistent pre and post training this enabled subjects to perform significantly more work in less time during the countermovement and, accordingly, this improved post countermovement performance by facilitating movement velocity throughout the action. The additional countermovement displacement also caused more work to be performed during the propulsion phase (greater range of motion from the lowest squat position to take-off), and because this the action was performed significantly faster. As more work was performed at a faster rate, propulsion mean power was also significantly greater.

The present findings contrast with reports of greater increases in peak, with respect to mean, CMJ metrics following strength-power training. For example, Cormie et al. (2010b) found improvements of 10.0% and 9.6% in peak and mean power respectively in strong individuals following a jump squat only training intervention, with similar results occurring in weaker individuals also. In alignment with this, a heavy back squat only training plan elicited improvements of 10.9% and 7.6% in peak and mean power (Cormie et al., 2010b) respectively. When considered alongside these present findings, this may suggest that some diversity in movement pattern and loading is needed if improvements in whole-phase CMJ measures are of priority. In support of this notion, a previous investigation (Potteiger et al., 1999) incorporating a variety of plyometric exercises (vertical jumping, bounding and depth jumps) resulted in improvements in mean power (5.5%) approximately twice that of peak power (2.8%). However, as none of these investigations compared multi-versus single modality resistance training, it is challenging to draw definitive conclusions. A possible explanation for these findings is the variation in the rate and magnitude of loading throughout the triple (hip, knee and ankle) extension in training enabled transfer to greater regions of the CMJ force-time curve (Suchomel, Comfort, & Lake, 2017; Suchomel, Comfort, & Stone, 2015). Multiple lifts in the present training intervention have differing regions of accentuated force application throughout the course of the movement at a given load (Figure 2), which is a key factor in training transfer (Suarez, Wagle, Cunanan, Sausaman, & Stone, 2019). For example, the jump squat commences with an unweighting period with its peak force occurring somewhat gradually at the completion of the lift, whereas the snatch grip pull commences with a steady acceleration before an unweighting and a rapid rise in force in the second half of the lift. A limitation of this single cohort study design was the inability to identify how CMJ phases are altered following mixed versus single modality resistance training. Future investigations are needed to better understand the nature of CMJ phase changes in response to different strength-power stimuli.

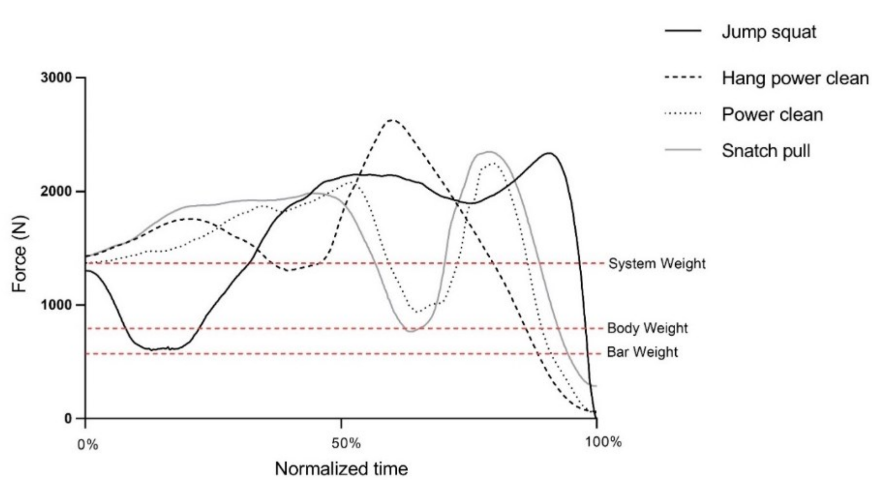

Figure 2: Case example of the normalised force-time curves of a subject across lifts included in the training intervention. All lifts in this figure were performed with the same bar mass.

These findings reinforce the need to focus on variables that consider performance over key phases and sub-phases. The focus on jump height or peak values of velocity and power may narrow the practitioner's or researcher's approach to CMJ force-time curve analysis by focusing on what amounts to a change in data that typically occurs in 1 ms (0.5 ms in this case, representing only 1.5% of mean propulsion duration).

Practical applications

- Where possible, practitioners should use CMJ variables beyond jump height and peak-form metrics.
- Phase/sub phase metrics provide critical insight into training induced adaptations that might otherwise be missed.

Conflict of Interest

The authors declare no conflict of interests.

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The effect of combined isometric and plyometric training on musculotendinous ankle stiffness and its subsequent effect on performance in international age-group track sprint cycling

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ABSTRACT

Within sprint cycling, the ankle's primary role is transferring power generated at the hip and knee. However, a stiffer musculotendinous unit around the ankle may directly contribute to increased performance. The aim of this study was to measure the influence of isometric and plyometric training on ankle stiffness and sprint cycling performance. Fifteen international age-group sprint track cyclists completed a 10-week intervention. An experimental group (n = 8) performed high-volume plyometrics and isometric calf raises in addition to their normal training, whilst a control group (n = 7) continued with no intervention. Kinetic measures were recorded on a force plate and in sprints on an isokinetic ergometer at 60 and 135 rev/min. Kinematic measures were recorded using high-speed cameras and reflective markers. Isometric peak force during plantar flexion and vertical ankle stiffness when hopping were both increased in the intervention group ($p \leq 0.05$). Bicycle sprints showed group differences in ankle stiffness ($p = 0.01$) at 135 rev/min and average ankle angle ($p = 0.04$) at 60 rev/min. Therefore, combined plyometrics and isometrics were an effective method for increasing ankle stiffness. This combination of stimuli also effected the utilisation of the ankle in sprint cycling.

1. Introduction

Track sprint cycling performance is determined by the relationship between propulsive power and resistance to forward motion (Martin et al., 2007). The latter is influenced by aerodynamics, mass, and rolling resistance or friction (Martin et al., 2007). Propulsive power depends on the linear relationship between pedalling rate (cadence) and torque at the pedal. Therefore, when all else remains equal, an increase in either peak pedalling rate or peak torque will elicit improvements in peak propulsive power. Whilst pedalling rate is reflective of coordinative and technical abilities, the ability to apply torque is largely determined by maximal neuromuscular force (Martin et al., 2007). This notion is supported by a body of evidence suggesting that maximal force production contributes to track sprint cycling performance (Barratt, 2014; Stone et al., 2004). As the largest instances of torque occur at low pedalling rates, start performance sees the highest contribution of maximal force production. As pedalling rate increases, the time available to apply force is reduced (downstroke <250 ms at 120 rev/min); consequently, the rapid production of force also becomes imperative to performance (Martin et al., 2007), particularly during flying sprint efforts.

The ankle's primary function during sprint cycling is to transfer power, produced at the knee and the hip, to the pedal (Kautz & Neptune, 2002; Kordi et al., 2017; Martin & Nichols, 2018; McDaniel et al., 2014). This notable action is demonstrated by the greater specific strength at the ankle displayed by elite track sprint cyclists when compared to sub-elite athletes (Barratt, 2014). Theoretically, improving the stiffness of the ankle joint should increase the capabilities of the ankle to transfer energy, created by the hip and knee, to the pedal. Previous research has shown stiffness to be related to increased performance in various sports, especially those associated with high levels of strength and power (Arampatzis et al., 1999; Belli & Bosco, 1992; Butler et al., 2003).

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In physics, stiffness is described by Hooke's law (F = kx) where F is the force required to deform an object, k is the proportionality constant and x is the distance the object is deformed. In physiological terms, stiffness is the ability of a joint or multi-joint system to resist deformation against an external force (Latash & Zatsiorsky, 1993). Therefore, increased stiffness could be achieved through an increase in either force production or a reduction in displacement at a joint or a combination of both. In cycling, an increase in stiffness will be seen through either a reduction in displacement or an increase in torque production.

Previously, increases in dynamic joint stiffness have been facilitated through either isometric or plyometric training interventions (Kubo et al., 2001, 2007, 2017) and to the best of our knowledge no study has utilised both training paradigms. A combination may increase the probability of adaptation, with research on the mechanism of musculotendinous changes still inconclusive (Burgess et al., 2007; Kubo et al., 2007, 2017). Therefore, the primary aim of this study was to assess the effect of both isometric and plyometric training on ankle stiffness, torque, and power, during sprints on a bicycle ergometer at low pedalling rates (60 rev/min) to indicate the effect on sprint cycling start performance. A secondary aim was to assess the effects of the intervention on performance during sprints on a bicycle ergometer at high pedalling rates (135 rev/min) to infer the effects on other aspects of sprint cycling.

2. Methods

2.1. Participants

International age-group sprint track cyclists (10.0-11.8 s flying 200 m time) participated in the study, consisting of an experimental group (EXP, 5 female and 3 male, 18 ± 1 years, 70.1 ± 12.3 kg, 1.71 ± 0.1m) and a control group (CON, 2 female and 5 male, 16 ± 1 years, 71.4 ± 7.5 kg, 1.72 ± 0.1m). Participants were allocated to groups by national governing body squad status, coaching group and location in the country. This meant that all those in the control group were younger, and that those in the experimental group were more highly trained. All participants were international age-group track sprint cyclists' and had 1-3 years resistance training experience. Participants were free from musculoskeletal injury for at least 12 months before the study started. Project approval was gained through the local university ethics committee, in line with the declaration of Helsinki. Parental or guardian assent was obtained for participants under the age of 18 years.

2.2. Procedures

This study used a non-randomised control trial design, which incorporated a 10-week intervention of high-volume plyometrics' and maximal isometric calf raises. Pre- and post-intervention measures of stiffness were recorded during sprints on an isokinetic cycle ergometer and during unilateral hopping on a force plate. Sprint cycling performance was also established pre- and post-intervention, using an isokinetic cycle ergometer at both low (60 rev/min) and high (135 rev/min) pedalling rates. Further measures of musculotendinous performance at the ankle were taken pre- and post-intervention to measure if changes in ankle strength that could influence cycling performance.

2.3. Ankle Stiffness

The methods and equipment used in this study to calculate ankle stiffness and other on-bike measures were based on previous research (Burnie et al., 2020). An isokinetic ergometer (SRM Ergometer, Julich, Germany) was set up to replicate each participant's track bicycle position, with a crank length of 165 mm. The modified ergometer flywheel was driven by a 2.2-kW AC induction motor (ABB Ltd, Warrington, UK). The motor was controlled by a frequency inverter equipped with a braking resistor (Model: Altivar ATV312 HU22, Schneider Electric Ltd, London, UK). This set-up allowed participants to start their sprints at the desired pedalling rate, rather than expending energy in accelerating the flywheel. The ergometer was fitted with Sensix force pedals (Model ICS4, Sensix, Poitiers, France) and a crank encoder (Model LM13, RLS, Komenda, Slovenia), sampling data at 200 Hz. Normal and tangential pedal forces were resolved using the crank and pedal angles into the effective (propulsive) and ineffective (applied along the crank) crank forces.

Riders undertook their standard warm-up on the ergometer at a self-selected pedalling rate and resistance for at least 10 min, followed by a warm-up sprint at 135 rev/min. Then riders performed two x 4 s seated sprints at a pedalling rate of 135 rev/min on the isokinetic ergometer with 4 min recovery between efforts. This process was repeated at 60 rev/min for each participant. 60 rev/min was the chosen pedalling rate as it is a rate required during standing start initial acceleration phase (Gardner et al., 2007), it has been used as a measure of cycling specific strength (Barratt, 2014).

Two-dimensional kinematic data of the participants' left side were recorded at 100 Hz using one high speed camera with infra-red ring lights (Model: UI-522xRE-M, IDS, Obersulm, Germany). The camera was perpendicular to the participant, centred on the ergometer and set 3 m away. For all sessions, the same researcher attached reflective markers on the pedal spindle, lateral malleolus, lateral femoral condyle, greater trochanter and iliac crest. Kinematics and kinetics on the ergometer were recorded by CrankCam software (Centre for Sports Engineering Research, SHU, Sheffield, UK), which synchronised the camera and pedal force data (down sampled to 100 Hz to match the camera data) and was used for data processing, including auto-tracking of the marker positions.

All kinetic and kinematic data were filtered using a Butterworth fourth order (zero lag) low pass filter, using a cut-off frequency of 8 Hz (Morrissey et al., 1995). Instantaneous left crank power was calculated from the product of the left crank torque and the crank angular velocity. Ankle angle was defined as the internal angle between the shank and foot segments. Ankle joint moments were calculated via inverse dynamics, using pedal forces, limb kinematics, and body segment parameters (de Leva, 1996). Ankle joint powers were determined by taking the product of the net ankle joint moment and ankle joint angular velocity. Data were analysed using a custom Matlab script (R2017a, MathWorks, Cambridge, UK). Each sprint lasted for 4 s, thus providing four and six complete crank revolutions at 60 rev/min and 135 rev/min, respectively. Crank forces and powers, ankle joint angles, moments and powers were resampled to 100 data points around the crank cycle and then mean value at each time point was calculated to obtain a single ensemble-averaged time series for each trial. Peak instantaneous crank power (PPO), peak effective crank force (FPE), peak ankle power (PANKLE), peak ankle extension moment (MANKLE) and average ankle angle over a complete crank revolution (AANKLE) were also calculated for each trial and averaged over the two trials in each session to obtain pre- and post-intervention. The ratio of change in joint moment to change in joint angle during dorsiflexion of the ankle in the downstroke of the crank cycle was calculated and used as the measure of on-bike ankle stiffness (KANKLE).

Off-bike vertical stiffness (KVERT) was established using an adaptation of previous protocols (McLachlan et al., 2006; Pena-González et al., 2019). The relationship between peak ground reaction force and the maximum displacement of centre of mass (taken from a marker on the anterior superior iliac spine) during the foot contact of a single hop was calculated to provide the metric. Participants were instructed to hop as high as they could with hands on hips, at a frequency greater than 2.2 Hz to ensure that the ankle joint was the primary regulator of stiffness (Farley & Morgenroth, 1999; Hobara et al., 2010, 2013). Data were collected once steady state hopping was achieved. Hopping trials were filmed on the sagittal plane from the left-hand side with a high-speed video camera, recording at 240 Hz (iPhone model 6s, Apple Inc. Cupertino, California, USA) and centre of mass displacement was calculated using Quintic video analysis software (Version 31, Quintic Consultancy Ltd. Birmingham, UK). Only one aspect of the body was filmed as no significant bilateral difference has been observed for unilateral hopping at this frequency (2.2 Hz) (Brauner et al., 2014; Hobara et al., 2013). This was consistent with the bicycle ergometer trials, where only the left side was filmed. The force data were collected on a force plate recording at 1000 Hz (NMP Technologies Ltd., London, UK).

2.4. Maximal Isometric Force

Peak Isometric force (FISO) was measured using a single-leg isometric standing calf raise performed on an adjustable rack. The rack was bolted to the floor and placed around the top of a Force Decks force platform unit (NMP Technologies Ltd., London, UK) measuring at 1000 Hz. Athletes were instructed to maintain neutral hip alignment and full extension of the knee and hip throughout the trial, with the bar resting on their shoulders. Coronal foot position and level of plantar flexion was self-selected to provide self-optimisation. The height of the bar was recorded for consistency across trials for each participant. The maximal isometric force was calculated from the mean of 3 x 5 s maximal contractions, interspersed by 30 s rest.

2.5. Concentric Mean Force

The average of two maximal straight legged concentric plantar flexion ‘jumps’ were also performed on the same force plate to provide a measure of concentric neuromuscular force (FCON). Participants were instructed to place hands on hips and jump with no countermovement, using aggressive plantar flexion. Full extension of the knee and hip were used throughout to ensure isolation of the plantar flexors. Concentric mean force was measured to align the protocol with studies of ankle strength and stiffness (Burgess et al., 2007). The participants performed three familiarisation sessions in the week prior to testing.

2.6. Intervention

The 10-week training intervention utilised both isometric and plyometric training. Isometric resistance training increases the stiffness of the tendon and muscles in the ankle; Gastrocnemius (GAS), Soleus (SOL), and Tibialis Anterior (TA). Improved muscle stiffness allows more lengthening of the tendon (Massey et al., 2018; McMahon et al., 2012), which will increase the storage of elastic energy. The training intervention consisted of two main exercises: maximal isometric calf raises and high-volume low-intensity plyometric contacts in the form of intensive pogo jumps that were progressed over 10 weeks (Table 1; Fouré et al., 2010; Jeffreys et al., 2019). EXP completed both protocols in conjunction with their regular programme, whilst CON continued their normal training.

Table 1: Protocol and progression used for isometric and plyometric interventions used by EXP.

Plyometric Protocol										
Week	1	2	3	4	5	6	7	8	9	10
Contacts per session	100	100	100	200	200	200	300	300	300	300
Total weekly contacts	300	300	300	600	600	600	900	900	900	900
Isometric Protocol										
Week	1	2	3	4	5	6	7	8	9	10
Volume per session	3 x 5 s	3 x 5 s	3 x 5 s	3 x 8 s	3 x 8 s	3 x 8 s	3 x 10 s	3 x 10 s	3 x 10 s	3 x 10 s
Total weekly volume	45 s	45 s	45 s	72 s	72 s	72 s	90 s	90 s	90 s	90 s

The overall content of the training programmes was prescribed collaboratively by the authors' and the participants cycling coaches. Cycling content included at least two track cycling sessions consisting of low-cadence technical standing starts and high-cadence, flying sprint efforts. One low-intensity road ride of about 45 to 60 minutes in length was also completed each week. Gym-based strength training sessions included traditional resistance training exercises: squats, leg press and deadlift. The weight lifted, number of repetitions, number of sets, and all supplementary exercises were prescribed by the authors.

2.7. Statistical Approach

Statistical analyses were performed using SPSS Statistics (Version 24, IBM, Chicago, Illinois, USA). A one-way ANCOVA with baseline as a covariate was used to assess the differences between groups for on-bike (KANKLE, PPO, FPE, PANKLE, MANKLE, AANKLE) and off-bike measures (KVERT, FCON, FISO). Where main effects of groups were found, a pairwise comparison was performed for the control and intervention group. Additionally, 95% confidence intervals (CI) and Cohen's effect sizes (d) were calculated to assess the magnitude of change from pre- to post-intervention. Effect sizes were interpreted using Cohen's classification system: effect sizes between 0.2 and 0.5 were considered small, between 0.5 and 0.8 were considered moderate, and greater than 0.8 were considered large (Cohen, 1969). The level of statistical significance was set to; $p \leq 0.05$ and all data is presented as group mean difference ± standard error (SE).

3. Results

3.1. Off-bike Measures

A group effect for was found for KVERT ($F(1,12) = 8.1$, $p = 0.02$), with greater KVERT post-intervention shown in the EXP (62.6 ± 22 N.cm-1, 95% CI [14.7, 110.5]) (Figure 1). The pre-to-post increase in KVERT was large in EXP (d = 1.20), whilst it was small in the control group (CON (d = 0.41). In FISO, a group effect was apparent ($F(1,12) = 4.9$, $p = 0.04$), with greater force shown post intervention in EXP compared to CON (173.6 ± 78.8 N; 95% CI [2, 345]) (Figure 1). Increases in EXP showed a moderate increase (d = 0.79) with only a trivial change in CON (d = 0.08). There was no group effect observed for FCON (Figure 1).

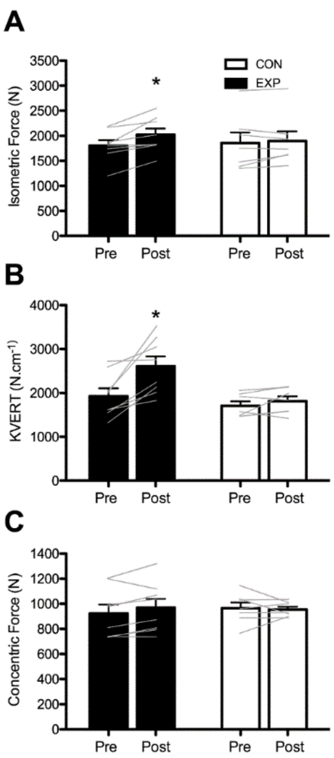

Figure 1: Individual responses and group mean changes from pre- to post-intervention. (A) Mean changes in FISO. (B) Mean changes in KVERT. (C) Mean changes in FCON. * denotes a significant difference between pre- and post-intervention measures ($p < 0.05$).

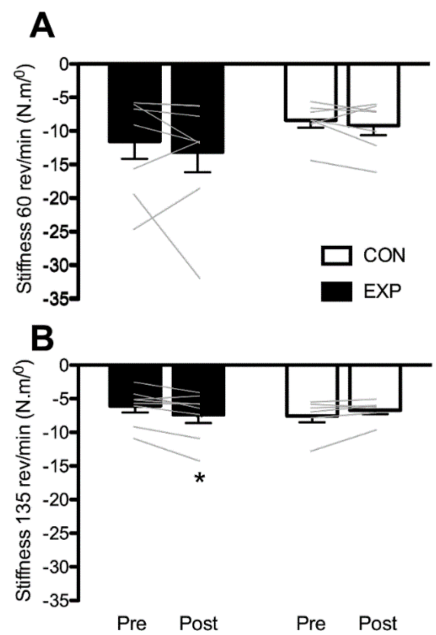

Figure 2: Individual and group mean traces for changes in ankle stiffness (KVERT) from pre- to post-intervention. (A) Mean and individual changes 60 rev/min (B) Mean and individual changes 135 rev/min * denotes a significant difference between pre- and post-intervention measures ($p < 0.05$).

3.2. Bicycle Isokinetic Ergometer Measures

In the 135 rev/min trials on the isokinetic ergometer, the one-way ANCOVA showed a group effect in KANKLE ($F(1,12) = 9.6$, $p = 0.01$), with pairwise comparisons showing EXP to be stiffer when compared to CON (2.1 ± 0.7 N.m/°, 95% CI [0.6, 3.5] (Figure 2). An increase was shown in the EXP (d = 0.45) compared to a decrease in the CON (d = -0.45). AANGLE, PPO, FPE, PANKLE, and MANKLE all showed no group effects in the 135 rev/min trials (Table 1). At 60 rev/min there was a group effect in AANGLE ($F(1,12) = 5.2$, $p = 0.041$) with the EXP showing a greater ankle angle through a crank cycle (2.9 ± 1.3°, 95% CI [0.1, 5.7]; Figure 3). EXP showed a moderate increase (d = 0.45) pre to post-intervention compared to a trivial change in CON (d = 0.01) group. There was no significant change in PPO at 60 rev/min ($F(1,12) = 4.45$, $p = 0.06$), with a small effect (d = 0.21) for CON, compared with a trivial change (d = 0.03) for EXP group. All other trials at 60 rev/min showed non-significant results (KANKLE, PPO, FPE, PANKLE, and MANKLE; Table 2).

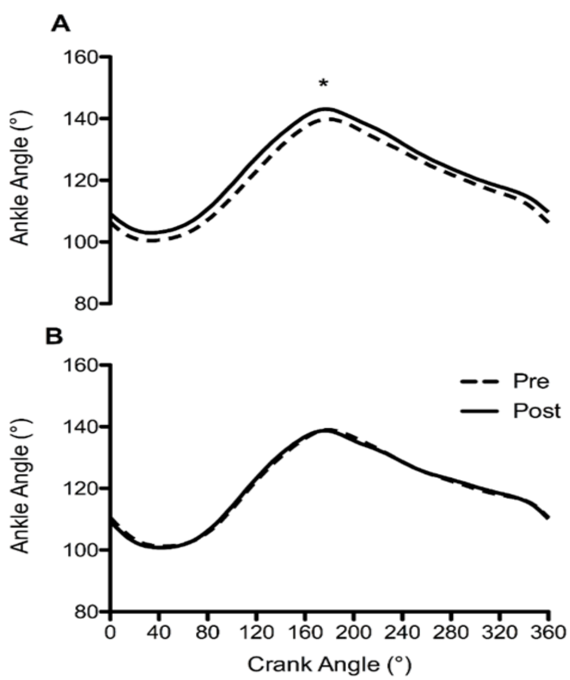

Figure 3. Group mean ankle angle throughout the crank cycle at 60 rev/min. (A) EXP (B) CON. * denotes a significant difference between pre- and post-intervention measures. compared the average ankle angle during a complete crank revolution (AANGLE) ($p < 0.05$)

4. Discussion

The main findings from this study were that combining plyometrics and isometric training increased vertical stiffness when hopping, and isometric force production at the ankle in a group of international age-group track sprint cyclists. During maximal cycling efforts, an increase in performance was not observed but ankle stiffness was increased at high cadence. The average ankle angle during a pedal cycle was also increased at the lower cadences that are representative of track sprint cycling starts.

4.1. Vertical Stiffness, Isometric Peak Force and Concentric Mean Force

Following the training intervention, there was a large increase in vertical stiffness of the ankle joint in the experimental group demonstrating that the training intervention was successful. Large increases in dynamic stiffness at a joint is in conjunction with previous research that facilitated either isometric or plyometric training interventions separately (Kubo et al., 2001, 2007, 2017). As research into the mechanism of musculotendinous changes is still inconclusive (Burgess et al., 2007; Kubo et al., 2007, 2017), a combination was used to increase the likelihood of adaptation. To the best of our knowledge this is the first study that has utilised both training paradigms.

Research has shown isometric exercise to cause optimal adaptations to elastic components of the musculotendinous unit (Kubo et al., 2001, 2007). Kubo et al. (2017) demonstrated that a plyometric intervention, similar to those used in this study, caused an adaptation to muscle fibre stiffness, whilst isometric interventions caused an increase in tendon stiffness. Conversely, (Burgess et al., 2007) compared the effect of a similar intervention on tendon stiffness and showed negligible differences in outcomes. Both protocols used in the current study have been shown to improve tendon stiffness, but there is mixed evidence regarding changes in musculature. Increases in the isometric measure would therefore infer adaptations to the tendinous component in the ankle. Consequently, any increases in concentric measures may indicate changes to musculature as the mechanism, due to the concentric only action negating any influence from the tendon (Kubo et al., 2001, 2007, 2017). The absence of any increase in concentric mean force from this study, indicates that the tendon rather than the musculature has been most influenced by the intervention. However, conclusions involving the mechanism of adaptation must be made with caution as the musculature and tendinous tissue in the musculotendinous unit is linked in a somewhat inextricable manner (Burgess et al., 2007; Oranchuk et al., 2019). Furthermore, the protocols used in the training intervention, consisting of bilateral hopping and maximal isometric calf raises, were similar kinematically to tests in which increases were seen.

4.2. Cycling Performance

Increases in ankle stiffness were seen at the pedalling rate of 135 rev/min. The comparable contact times in the pogo jumps and time available to apply force at 135 rev/min (both <250 ms) might have been a contributing factor. This connection provides further indication of a tendinous response to the intervention. Increases in cycling specific performance (peak crank power and peak effective force) were not seen at 135 rev/min but the evidence presented below suggest that the changes caused may enhance the

Table 2: Group mean and standard error for all non-significant variables from bicycle ergometer.

60 rev/min										
	K_{ANKLE} (N.m/°)		F_{PE} (N)		PPO (W)		M_{ANKLE} (N.m)		P_{ANKLE} (W)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
EXP	-11.6 ± 2.6	-13.2 ± 3.0	919.8 ± 60.3	966.6 ± 52.2	921.1 ± 55.7	926.0 ± 42.9	121.1 ± 9.9	127.6 ± 8.4	315.7 ± 16.4	328.3 ± 21.9
CON	-8.5 ± 1.1	-9.2 ± 1.4	974.0 ± 78.3	1044.6 ± 64.3	1037.5 ± 104.9	1084.9 ± 68.0	138.4 ± 8.0	137.4 ± 12.7	404.6 ± 34.5	371.1 ± 26.8
135 rev/min										
	A_{ANGLE} (°)		F_{PE} (N)		PPO (W)		M_{ANKLE} (N.m)		P_{ANKLE} (W)	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
EXP	122.3 ± 2.1	123.8 ± 2.0	641.0 ± 42.8	648.8 ± 39.2	1447.5 ± 121.4	1538.9 ± 72.3	83.3 ± 8.5	86.1 ± 7.6	362.2 ± 42.6	362.6 ± 39.7
CON	132.0 ± 1.4	122.1 ± 1.6	688.5 ± 55.1	717.1 ± 52.6	1441.3 ± 138.2	1595.7 ± 140.1	95.5 ± 7.4	97.2 ± 8.5	384.4 ± 45.0	419.8 ± 48.2

Note. K_{ANKLE}, Ankle stiffness (60 rev/min only); A_{ANGLE}, Ankle angle (135 rev/min only); F_{PE}, Peak effective force; PPO, Peak power; M_{ANKLE}, Ankle moment; P_{ANKLE}, Ankle power.

efficiency of power production at the ankle with a period of cycling specific training. Increased stiffness has consistently been shown to have a positive impact on performance in other explosive strength and power sports (Arampatzis et al., 1999; Belli & Bosco, 1992; Bret et al., 2002). McDaniel et al. (2014) demonstrated that as pedalling rate increases the contribution of the ankle to crank power reduces, which may be a partial explanation for the absence of increase in peak crank power and peak effective force at 135 rev/min. An increase in ankle stiffness with no significant increase in ankle moment suggests that less displacement has occurred at the joint. Reducing the displacement of the ankle joint during cycling has been shown to occur with practice, and to coincide with an improvement in the efficiency of pedalling (Hasson et al., 2008). If the physiological capability of the lower limbs is increased further, then a performance increase may occur. In well-trained athletes, the magnitude and time course of adaptations is smaller and slower than the non-trained population (Till et al., 2017), indicating that these effects could be optimised further by a longer or more intense training period.

An increase in average ankle angle, but not ankle stiffness, occurred at lower pedalling rate. At 60 rev/min a more plantar flexed position was utilised by the cyclists following the intervention, but changes in displacement and ankle moments were not found. These findings are comparable to those found after the implementation of single-leg cycling drills (Hasson et al., 2008) and suggests that the intervention may have facilitated an enhancement in pedalling, but through improvements in musculotendinous qualities rather than coordination. The absence of any increase in ankle stiffness at 60 rev/min may be due to reduced transfer of physiological qualities to the lower pedalling rate trials. During a sprint cycling start, where lower pedalling rates are experienced, the cyclist will be in a standing position and would not become seated until a higher pedalling rate was reached.

Unfortunately, this position cannot be replicated reliably on a bicycle ergometer and, consequently, all efforts are performed seated (Wilkinson et al., 2020). Biomechanical specificity has been consistently shown to be an important aspect of transfer of training in elite athletes. Factors that contribute to transference include; contraction type, joint angle, posture and limb position, and velocity of contraction (Morrissey et al., 1995; Stone et al., 2004; Wilson et al., 1996). During the 60 rev/min trials, participants were performing a skill with familiar contraction types and velocities but unfamiliar joint angles, limb angles, and posture. This may provide an explanation for the adaptation in vertical stiffness not having transferred as effectively to lower pedalling rates when compared to higher pedalling rates that were completed in a seated bicycle position.

At 60 rev/min, increases in PPO by CON approached significance, and the effect size was large. This might have been caused by the younger training and chronological age of the athletes in this group, rather than any effect of the intervention. Larger adaptations are consistently shown by less mature athletes or athletes of younger training age for strength and power training (Pena-González et al., 2019; Till et al., 2017). However, this makes adaptations in the other variables measured, by the older, more highly trained group following the intervention more noteworthy. Lower-body maximal force production is correlated to peak power output and performance in sprint cycling (Stone et al., 2004). Like in any other sport, there is a coordinative aspect, and stronger athletes must be able to apply force in a specific modality. To improve ankle performance on a bike, it has been suggested that specific learning in a cycling modality is needed (Hasson et al., 2008; Kordi et al., 2017; McDaniel et al., 2014). This research suggests changes can occur through more general training. These structural qualities may provide the foundation for later coordinative properties to be built upon in a more specific modality (Flanagan & Comyns, 2008). Increases in average ankle angle seen at 60 rev/min could also provide a future benefit to performance through efficiency. Anderson et al. (2007) showed through mathematical modelling that larger voluntary torques are created at larger ankle angles. Increases in ankle angle will allow athletes to increase forces expressed by the ankle. Assuming change in angle does not affect the contribution from limbs further up the chain, force applied to the pedal will increase and ultimately improve sprint cycling performance. Therefore, a performance increase may occur with further specific sprint cycling practice or with a longer intervention to allow for maximal transfer of training (Till et al., 2017; Young, 2006).

Combined high volume plyometric hopping and isometric strength training is an effective method for increasing stiffness and force production at the ankle in international age-group sprint track cyclists. Similar interventions are recommended for those seeking to enhance performance in sprint track cycling and may offer benefits to other sports requiring high levels of ankle stiffness. Coaches working with sprint track cyclists should consider the use of a plyometric and isometric calf raises in additional to the athletes' traditional track cycling and strength training programmes.

Conflict of Interest

The authors declare no conflict of interests.

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Maximal isometric force in the start of the first pull exhibits greater correlations with weightlifting performance than in the mid-thigh position in national and international weightlifters

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A B S T R A C T

This investigation compared the maximal isometric force capacity between the start position of the first pull (IPSP) and isometric mid-thigh pull (IMTP), and their relationship with weightlifting competition performance in twenty national and international, male and female weightlifters. Isometric strength assessment and competition performance data collected as part of the routine sport science services of a national weightlifting performance programme were used for this study. Differences in isometric peak force (PkF) and allometrically scaled peak force (PkFa) between the IPSP and IMTP were evaluated using a paired-samples t-test. The relationships between absolute and allometrically scaled IPSP, IMTP, Total (TOT), Snatch (SN) and Clean & Jerk (CJ) variables were analysed using Pearson's Product-Moment Correlation. Fisher's r-to-z transformation was used to statistically compare the correlation values between the IPSP and IMTP with weightlifting performance measures. The IMTP PkF and PkFa were significantly greater than the IPSP PkF and PkFa, respectively, across combined (COM), male (M) and female (F) groups ($p = < 0.001$). However, the IPSP PkF exhibited significantly greater correlations with SN ($r = 0.94$ vs. 0.83, $p < 0.05$) and TOT ($r = 0.95$ vs. 0.86, $p < 0.05$) than the IMTP PkF in the COM group. In addition, the IPSP PkFa exhibited a significantly greater correlation with allometrically scaled snatch (SNa) ($r = 0.83$ vs. 0.51, $p < 0.05$) than the IMTP PkFa in the COM group. No significant correlations were observed between the IPSP PkFa and IMTP PkFa across M, F and COM groups. These findings suggest that the maximal force capacity in the IPSP is a greater determinant of weightlifting performance than in the IMTP, however, each may be representative of independent neuromuscular qualities. Coaches and practitioners working with weightlifters may consider implementing the IPSP assessment in addition to the IMTP to evaluate the strength characteristics specific to the different phases of the pull.

1. Introduction

The snatch and the clean & jerk techniques are initiated with the 'pull' phase, where the bar is displaced from the floor to waist height; and vertical propulsive forces are applied to project the bar high enough to be caught in an overhead (Snatch) or front rack (Clean) position (Kipp & Giordanelli, 2018). The pull is comprised of three sub-phases: the first pull, transition and second pull, each exhibiting unique kinetic and kinematic characteristics (Gourgoulis, Aggeloussis, Garas, & Mavromatis, 2009). The first pull is integral to the efficiency of the lift, as precise barbell and joint mechanics can limit excessive external joint torque and preserve balance between the center of mass and base of support. This facilitates a more efficient transition phase and subsequently a greater application of vertical ground reaction forces (VGRF) in the second pull (Favre & Peterson, 2012).

The first pull occurs between the separation of the bar from the floor and the peak extension of the knee, finishing with the bar slightly above the patella. The lifter therefore must generate tension, overcome inertia, and accelerate the bar vertically by

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extending the legs whilst maintaining a constant torso angle relative to the floor (Chavda & Turner, 2020). This requires a large concentric knee extensor torque from a flexed knee angle, while resisting notable external joint torque around hip and lower back (Kipp, Redden, Sabick, & Harris, 2012).

Previous investigations have shown that peak VGRF during the first pull strongly correlate with the load lifted in the snatch and clean lifts (Baumann, Gross, Quade, Galbierz, & Schwirtz, 1988; Enoka, 1979; Souza, Shimada, & Koontz, 2002). Elite weightlifters also demonstrate greater relative peak VGRF during the first pull than their sub-elite counterparts (Kauhanen, Häkkinen, & Komi, 1984). In addition, smaller horizontal resultant acceleration vectors applied to the bar in the first pull are associated with greater technical efficiency and overall success rate in the snatch (Gourgoulis et al., 2009). These findings emphasize the importance of both the magnitude and vertical direction of force application during this phase and consequently, are critical considerations when evaluating phase-specific neuromuscular characteristics in weightlifters.

The existing dynamic and isometric assessments used to evaluate the neuromuscular characteristics in weightlifters are typically based upon their kinetic and kinematic specificity to the second pull (Carlock et al., 2004; Haff et al., 2005, 1997). The most widely investigated assessment is the isometric mid-thigh pull (IMTP), which evaluates the maximal VGRF and rate of force development (RFD) in an identical position to the start of the second pull (Comfort et al., 2019). This position was adopted because the greatest VGRF and RFD occurs during this phase (Haff et al., 1997). In addition, this position corresponds with the peak of the strength curve (Stone et al., 2019) which is proposed to be the optimal position for maximal isometric testing (Wilson & Murphey, 1996). Multiple investigations have demonstrated large correlations between the IMTP peak force (PkF) and RFD with weightlifting performance in sub-elite and elite male and female weightlifters ($r = 0.58$ to 0.84), reinforcing the importance of these qualities in the second pull (Beckham et al., 2013; Haff et al., 2005; Joffe & Tallent, 2020; Stone et al., 2005). However, differences in joint angles, external joint torque (Kipp et al., 2012) and temporal patterns of VGRF (Chavda et al., 2020) between the first and second pull gives rise to the supposition that the assessment of maximal force characteristics specific to the first pull may reveal additional information regarding the neuromuscular characteristics associated with superior weightlifting performance. In a recent review on the use of the IMTP in weightlifters, Stone et al. (2019) proposed conducting a maximal isometric assessment across multiple positions of the pull, including the start position of the clean or snatch lifts. It was suggested that this information could inform the prescription of training by addressing position-specific strength deficits in the pull. However, no investigations to date appear to have addressed this notion, therefore our understanding of the role of maximal force capacity in the start of the first pull is unclear.

However, several investigations have examined isometric testing across multiple positions of the corresponding dynamic exercise, including the deadlift (Bartolomei et al., 2019; Beckham et al., 2012; Malyszek et al., 2017; Miller, 2020), back squat (Bazyler, Beckham, & Sato, 2015; Marcora & Miller, 2000) and bench press (Murphy, Wilson, Pryor, & Newton, 1995). A common finding between these investigations was that the longer muscle length testing position elicited a comparatively smaller peak force than at the shorter muscle length position. This is likely attributed to each of these exercises being categorized as having ‘ascending strength curves’ (McMaster, Cronin, & McGuigan, 2009). Interestingly however, those investigations which examined the correlations between isometric PkF at different testing positions with the exercise 1-repetition maximum (1-RM), consistently revealed greater correlations between the peak force in the longer muscle length position (Bartolomei et al., 2019; Bazyler et al., 2015; Miller, 2020; Wilson & Murphey, 1996). These findings are perhaps expected, given that the weakest mechanical position is the theoretical limit for the maximal load that can be lifted in a dynamic movement. Although the snatch and clean are most appropriately categorized as ballistic tasks, rather than a maximal dynamic strength task, their shared objective is to lift a maximal weight. It is therefore plausible that this principle applies to these lifts as well. Like these previous reports, an isometric pull in the start position of the weightlifting movements may reveal greater correlations with weightlifting performance that the IMTP.

The purpose of this investigation is to compare the relationships between an isometric pull from the start position of the first pull (IPSP) and the IMTP with weightlifting competition performance in national and international male and female weightlifters. It is hypothesized that the IPSP will exhibit a lower maximal force output but will reveal a stronger correlation with weightlifting performance measures compared with the IMTP.

2. Methods

This investigation examined the relationship between the IPSP and IMTP with weightlifting competition performance including the Snatch (SN), Clean & Jerk (CJ) and Total (TOT) in national and international male and female weightlifters. Force-platform strength assessment and competition performance data collected as part of the routine sports science support services of a national weightlifting performance and talent development programme between 2014 and 2017 were utilised for this investigation. Testing took place during specific competition preparation camps at the beginning of training sessions. Testing data within four to eight weeks of a national or international competition were collected for analysis.

2.1. Participants

Twenty national and international male and female weightlifters (7 males; age: 24.2 years ± 3.0; weight: 85.5 kg ± 13.1; height: 1.76 m ± 0.06 and 13 females; age: 26.1 years ± 7.2; weight: 62.2 kg ± 8.5; height: 1.57 m ± 0.07) participated in this investigation. All participants were part of the national weightlifting performance programme or talent development programme at the time of data collection. All participants provided informed consent to the use of these data. Project approval was obtained from a University Ethics Committee.

2.2. Procedure

2.2.1. Isometric Pull Assessments

Isometric testing was performed using a ForceDecks bilateral force plate system (2 x 350 mm x 750 mm ForceDecks FD4000 Force Platforms, NMP Technologies, London, UK) inside a customised power rack with bar attachment points located at 2.5 cm intervals along the vertical bar supports. Force-time data were captured with a sampling frequency of 1000 hz using NMP ForceDecks software (Version 1.2.6322, NMP Technologies, London, UK). Testing took place at the beginning of training sessions following a standardised warm-up protocol which included dynamic movements (i.e., body weight squats and lunges), technical drills with an empty bar and a series of warm-up attempts in either the snatch or clean & jerk, depending on the athlete's training programme.

The set-up position for the IMTP test was established in accordance with previously described guidelines (Comfort et al., 2019). Knee and hip angles ranged between 125 to 145° and 140 to 150° respectively, and the bar held in a clean grip with the torso oriented vertically. The bar was positioned with slight contact on the upper thigh to ensure a kinematic similarity to the start of the second pull. Feet were positioned directly beneath the center of the bar and approximately hip-width apart. For the IPSP, the bar height was consistent for all participants as this was based on the height of a weightlifting bar when loaded with standard weightlifting disks of 45 cm diameter. Therefore, the center of the bar was positioned 22.5 cm from the floor. This meant that each participant's body position, such as knee and hip joint angles, might have varied slightly, depending on individual anthropometric and mobility characteristics. However, key technical criteria of the set-up position for the clean were adhered to, which included bar positioned directly above the metatarsophalangeal joint, center of the hip joint above the center of the knee joint, center of the shoulder joint above the center of the hip joint, center of the shoulder joint directly above or slightly in advance of the bar and the arms remained full extended (Figure 1) (Chavda et al., 2020). This was visually inspected by the administrator prior to the commencement of the test. Similarly, to the IMTP protocol, a clean grip was adopted for this assessment.

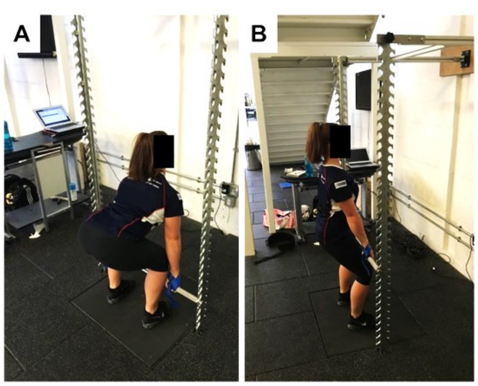

Figure 1: Example testing positions for the Isometric Pull from the Start Position (A) and the Isometric Mid-Thigh Pull (B).

Weightlifting shoes and lifting straps were utilized and standardized for both isometric tests. All participants were familiar with both testing protocols; therefore, a single warm-up attempt was performed before their first maximal attempt of each test. As these assessments formed part of a physical testing battery for the athletes, the order of the isometric assessments was standardized, so that the IMTP was performed before the IPSP. This was to avoid any confounding factors which may lead to greater error when trying to detect a meaningful change over time (McGuigan, 2020). Before each test, participants were instructed to "pull as hard and fast as possible" and "keep pulling until you are signaled to release" (Comfort et al., 2019). One second after the force trace either plateaued or continued to decline, a signal to cease the test was given. Each test lasted approximately 2 to 4 seconds. Three tests were performed for each athlete with 3 minutes rest between attempts. The net PkF was collected and the average value of all the three trials was used for the analysis. Test-retest reliability for IMTP and IPSP for PF was ICC = 0.97, CV 2.76% and ICC = 0.98, CV 1.3% respectively, and are consistent with previous reports (Beckham et al., 2012; Haff et al., 2005; Joffe & Tallent, 2020; Stone et al., 2005).

2.2.2. Competition Performance Data Collection

Competition performance data including SN, CJ and TOT were collected from national championship events, international IWF sanctioned events and the European Under 23s (A non-IWF sanctioned event) between 1st January 2014 and 31st December 2017. These competitions were chosen because it was typical for athletes to 'peak' for these competitions, and thus, it was reasoned that these performances reflected their optimal athletic performance. Competition performance data were obtained from the publicly available British Weight Lifting, International Weightlifting Federation and European Weightlifting Federation websites. Test-retest reliability of weightlifting performance in international male and female weightlifters has been reported as 2.5% (95% CI 2.2 to 2.9%) and 3.2% (95% CI 2.7 to 4.1%) respectively (McGuigan & Kane, 2004).

2.3. Statistical Approach

All data are presented as mean ± standard deviation. Strength assessment and competition performance data were tested for normal distribution using the Shapiro-Wilks test. All analyses were performed on absolute and allometrically scaled assessment (IPSP and IMTP, IPSPa and IMTPa, respectively) and competition data (SN, CJ, TOT and SNa, CJa, TOTa, respectively). Allometric scaling of isometric strength and weightlifting performance to body mass was performed using the power exponent of 0.67 (Jaric, Irkov, & Arkovic, 2005). A paired-samples t-test was used to analyze the difference between IPSP and IMTP and an independent-samples t-test was used analyze the differences between male and female groups, each with 95% confidence intervals and effect sizes. The relationship between all competition performance variables (SN, CJ, and TOT) with IPSP and IMTP was investigated using the Pearson's Correlation Coefficient. Correlation values are presented with 95% confidence intervals. Correlations were interpreted in accordance

Table 1: Mean ± SD of absolute and allometrically scaled weightlifting performance measures and isometric pull assessments.

Group	TOT (kg)	SN (kg)	CJ (kg)	IMTP PkF (N)	IPSP PkF (N)	TOTa ($kg.kg^{0.67}$)	SNa ($kg.kg^{0.67}$)	CJa ($kg.kg^{0.67}$)	IMTP PkFa ($N.kg^{0.67}$)	IPSP PkFa ($N.kg^{0.67}$)
M (7)	282 ± 46	128 ± 20	154 ± 27	3324 ± 664	1874 ± 357	14.58 ± 1.13	6.60 ± 0.47	7.78 ± 0.73	168.00 ± 20.59	94.78 ± 10.16
F (13)	165 ± 25	73 ± 11	92 ± 15	2272 ± 540	1211 ± 235	10.79 ± 1.16	4.75 ± 0.51	6.04 ± 0.69	142.50 ± 20.60	75.8 ± 10.20
COM (20)	206 ± 66	92 ± 30	114 ± 36	2640 ± 767	1443 ± 425	12.11 ± 2.17	5.40 ± 1.03	6.71 ± 1.17	151.40 ± 28.30	82.40 ± 13.10

TOT = Total; SN = Snatch; CJ = Clean & Jerk, TOTa = allometrically scaled Total; SNa = allometrically scaled Snatch; CJa = allometrically scaled Clean & Jerk; IPSP = Isometric Pull from Start Position; IMTP = Isometric Mid-Thigh Pull; PkF = Peak Force; PkFa = Allometrically Scaled Peak Force

with the following descriptive criteria: 0 = *trivial*, 0.1 = *small*, 0.3 = *moderate*, 0.5 = *large*, 0.7 = *very large*, 0.9 = *nearly perfect*, 1 = *perfect* (Hopkins, Marshall, Batterham, & Hanin, 2009). To evaluate the differences between correlations, all values were converted using Fishers r-to-z transformation. The comparison of correlations between independent groups (M vs. F) was done in accordance with the method described by Cohen, Cohen, West, and Aiken (2003). The comparison of correlations within groups (IPSP vs. IMTP) was done in accordance with the method described by Steiger (1980). Alpha was set at 0.05. All t-tests and correlation analyses were performed using SPSS (version 24.0). The analysis of comparisons between correlation values were performed in a customized Microsoft Excel spreadsheet (Version 2012).

3. Results

3.1. Comparisons between IPSP and IMTP

The mean ± SD for all strength assessment and performance variables are presented in Table 1. Significant differences were observed between the IPSP PkF and the IMTP PkF for the M (1449.2 ± 454.2 N, 95% CI = 1029.1 to 1869.3, t(6) = -8.442, $p < 0.001$, ES = 3.19), F (1060.5 ± 464.9 N, 95% CI = 779.6 to 1341.4, t(12) = -8.225, $p < 0.001$, ES = 2.06) and COM groups (1196.6 ± 487.7 N, 95% CI = 968.3 to 1424.8, t(19) = -10.973, $p < 0.001$, ES = 2.45) (Figure 2). Similarly, significant differences were observed between IPSP PkFa and IMTP PkFa for the M (73.22 ± 18.89 $N.kg^{67}$, 95% CI = 55.75 to 90.70, t(6) = -10.252, $p < 0.001$, ES = 3.88), F (66.69 ± 29.02 $N.kg^{67}$, 95% CI = 49.15 to 84.23, t(12) = -8.284, $p < 0.001$, ES = 2.30) and COM groups (69.98 ± 25.60 $N.kg^{67}$, 95% CI = 57.00 to 80.96 t(19) = -12.052, $p < 0.001$, ES = 2.69) (Figure 2). No significant differences were observed between the M and the F groups for the IPSP:IMTP ratio (1.94 ± 4.45 %, 95% CI = -11.30 to 7.40, t(18) = -10.973, $p = 0.204$, ES = 0.2) (Figure 3).

3.2. Correlations between IPSP, IMTP and weightlifting performance measures

All results from the correlation analysis are presented in Tables 2 and 3. The analysis between IPSP PkF and weightlifting performance variables revealed *nearly perfect*, *very large* to *nearly perfect*, and *very large* correlations for the COM, M and F groups, respectively. The analysis between IMTP PkF and weightlifting performance variables revealed *very large*, *very large* to *nearly perfect* and *large* correlations for the COM, M and F groups, respectively (Figure 4). The analysis between IPSP PkFa and allometrically scaled weightlifting performance variables revealed *very large, large* to *very large* and *large* correlations for the COM, M and F groups, respectively. The analysis between IMTP PkFa and allometrically scaled weightlifting performance variables revealed *large*, *moderate* to *very large* and *small* correlations for the COM, M and F groups, respectively (Figure 4). The correlation between the IPSP PkF and IMTP PkF in M and COM groups were *very large*. No significant correlation between IPSP PkF and IMTP PkF was observed in the F group. No significant correlations were observed between the IPSP PkFa with IMTP PkFa in either M, F or COM groups.

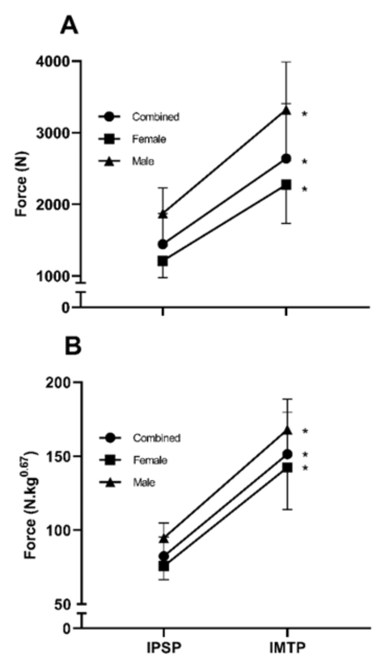

Figure 2: Absolute (A) and allometrically scaled (B) difference between IPSP and IMTP for male, female and combined male and female groups. IPSP = Isometric Pull from Start Position, IMTP = Isometric Mid-Thigh Pull. * denotes $p < 0.001$.

3.3. Comparison of correlations between IPSP and IMTP with weightlifting performance measures

A significantly greater correlation was observed between the IPSP PkF with SN and TOT compared with the IMTP PkF (Z = 2.16, p = 0.04 and Z = 2.05, p = 0.03, respectively). Furthermore, a significantly greater correlation was observed between IPSP PkFa with SNa compared with the IMTP PkFa (Z = 2.08, p = 0.04).

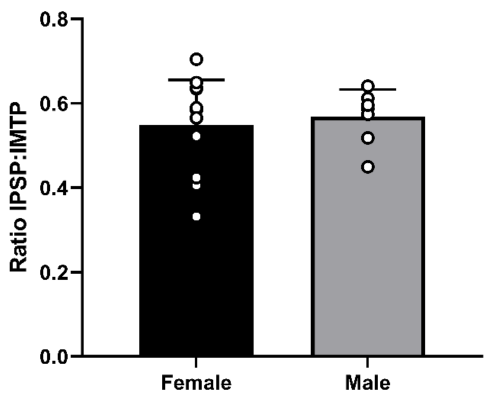

Figure 3: Group average and individual ratio between IPSP: IMTP for males and females. IPSP = Isometric Pull from Start Position, IMTP = Isometric Mid-Thigh Pull. Ratio IPSP: IMTP = IPSP ÷ IMTP. White circles denote individual data.

4. Discussion

The aim of this investigation was to compare the relationships between the IPSP and IMTP with weightlifting competition performance in national and international weightlifters. A critical finding of this investigation was that despite the IPSP exhibiting a comparably smaller PkF than the IMTP, IPSP PkF demonstrated a stronger relationship with SN and TOT in the COM group. Furthermore, when allometrically scaled to body mass, the IPSP PkFa also showed a stronger relationship with SNa in the COM group. These findings suggest that the maximal isometric force capacity in the start position of the first pull is a greater determinant of weightlifting performance than at the start of the second pull.

To date, no empirical investigations have examined the relationship between the IPSP with measures of weightlifting performance. However, several investigations have reported similar *large* to *nearly perfect* correlation values between IMTP PkF with SN, CJ and TOT (r = 0.82 to 0.93, r = 0.81 to 0.83, r = 0.80 to 0.82, respectively) (Beckham et al., 2013; Haff et al., 2005; Joffe & Tallent, 2020; Stone et al., 2005). A number of these investigations also examined the relationship between allometrically scaled IMTP PkFa and SNa, CJa and TOTa, reporting *moderate* to *very large* correlations (r = 0.50 to 0.79, r = 0.50 to 0.77, r = 0.78, respectively), which are generally higher than those reported in the present investigation (Beckham et al., 2013; Stone et al., 2005). However, the correlations between IPSP PkFa with allometrically scaled performance measures were similar to or greater than previous reports in the IMTP PkFa, ranging between *large* to *very large* correlations. To the best of the author's knowledge, the correlations between IPSP with weightlifting performance in the present investigation are the highest reported between a maximal isometric assessment and SN, CJ and TOT in the literature to date, bringing forth a potentially more accurate surrogate measure to of weightlifting performance potential.

Our findings support the already extensive evidence for the use of maximal isometric strength testing in multi-joint, biomechanically specific positions, as they elicit high correlations with corresponding dynamic sporting movements (Comfort et al., 2019; Lum, Haff, & Barbosa, 2020; Wilson & Murphey, 1996). However, these findings appear to conflict with the recommendation that maximal isometric testing should be conducted at the peak of the strength curve (Wilson & Murphey, 1996). The rationale for this is based on the notion that this standardised position should reduce the variability in force output associated with the error in determining specific joint angles for testing (Wilson & Murphey, 1996) and that it coincides with the region where VGRF and RFD are optimised in the corresponding dynamic movement (Haff et al., 1997; Wilson & Murphey, 1996). The latter point implies that this position would exhibit a greater correlation with dynamic performances compared with testing at other joint angles.

Interestingly however, in the present investigation the weakest pull position (IPSP) elicited greater correlations with weightlifting performance. Similar findings were reported by Bazyler et al. (2015) who investigated the relationship between maximal isometric squat PkF at 90° and 120° knee angles with the back squat 1-RM. Despite showing a significantly greater PkF in the 120° knee angle, the isometric PkF in the 90° knee angle demonstrated a *very large* and a considerably greater correlation with back squat 1-RM (r = 0.86 vs. 0.60). Several investigations have reported similar findings showing isometric PkF to be greater in the shorter muscle length conditions, yet a greater correlation observed between PkF in the longer muscle length condition with the corresponding exercise 1-RM (Bartolomei et al., 2019; Miller, 2020; Murphy et al., 1995).

On the contrary, Marcora and Miller (2000) examined the relationship between isometric PkF and peak RFD in the back squat at 90° and 120° knee angles with countermovement jump (CMJ) and squat jump (SJ) height. No correlations were observed between PkF at 90° or 120° knee angle with either jump, however peak RFD in the 120° knee angle exhibited *large* to *very large* correlations with CMJ and SJ height (r = 0.69 and 0.71, respectively). Moreover, no correlations were reported with peak RFD in the 90° knee angle, indicating that the peak RFD at comparatively shorter muscle lengths exhibit greater correlations with similar ballistic dynamic performance compared with peak RFD at longer muscle lengths. Similar findings were reported by Rousanoglou, Georgiadis, and Konstantinos (2008), showing RFD at shorter muscle length in the isometric leg extension exhibited greater correlations with jumping performance, compared with longer muscle lengths.

Table 2: Correlations with 95% CI's, between absolute and allometrically scaled IPSP, IMTP and Weightlifting Performance Measures

		IPSP PkF			IMTP PkF	
	r value	95% CI	Descriptor	*r* value	95% CI	Descriptor
SN COM	0.94 ** #	0.85 - 0.98	*nearly perfect*	0.83 **	0.61 - 0.93	*very large*
CJ COM	0.95 **	0.88 - 0.98	*nearly perfect*	0.88 **	0.72 - 0.95	*very large*
TOT COM	0.95 ** #	0.88 - 0.98	*nearly perfect*	0.86 **	0.67 - 0.94	*very large*
SN M	0.96 **	0.75 - 0.99	*nearly perfect*	0.77 *	0.04 - 0.96	*very large*
CJ M	0.89 **	0.42 - 0.98	*very large*	0.91 **	0.50 - 0.99	*nearly perfect*
TOT M	0.93 **	0.59 - 0.99	*nearly perfect*	0.87 *	0.34 - 0.98	*very large*
SN F	0.81 **	0.47 - 0.94	*very large*	0.60 *	0.07 - 0.87	*large*
CJ F	0.85 **	0.56 - 0.95	*very large*	0.69 **	0.22 - 0.90	*large*
TOT F	0.85 **	0.56 - 0.95	*very large*	0.66 **	0.17 - 0.89	*large*
		IPSP PkFa			IMTP PkFa	
	r value	95% CI	Descriptor	*r* value	95% CI	Descriptor
SNa COM	0.83** #	0.61 - 0.93	*very large*	0.51*	0.09 - 0.78	*large*
CJa COM	0.85**	0.65 - 0.94	*very large*	0.65**	0.29 - 0.85	*large*
TOTa COM	0.85**	0.65 - 0.94	*very large*	0.59**	0.20 - 0.82	*large*
SNa M	0.81*	0.15 - 0.97	*very large*	0.33	-0.56 - 0.87	*moderate*
CJa M	0.69	-0.13 - 0.95	*large*	0.79*	0.09 - 0.97	*very large*
TOTa M	0.78*	0.78 - 0.97	*very large*	0.64	-0.22 - 0.94	*large*
SNa F	0.52	-0.04 - 0.83	*large*	0.28	-0.32 - 0.72	*small*
CJa F	0.65**	0.15 - 0.88	*large*	0.47	-0.11 - 0.81	*small*
TOTa F	0.62**	0.10 - 0.87	*large*	0.40	-0.19 - 0.78	*small*

IPSP = Isometric Pull from Start Position, IMTP = Isometric Mid-Thigh Pull, PkF = Peak Force, PkFa = Allometrically Scaled Peak Force, SN = Snatch, CJ = Clean & Jerk, TOT = Total, SNa = Allometrically Scaled Snatch, CJa = Allometrically Scaled Clean & Jerk, TOTa = Allometrically Scaled Total, COM = Combined Male and Female group, M = Male group, F = Female group. * = $p < 0.05$; ** = $p < 0.01$ denotes statistically significant correlations. # = $p < 0.05$ denotes statistically significant difference between IPSP and IMTP correlation.

Table 3: Correlations with 95% CI's, between absolute and allometrically scaled IPSP and IMTP variables for male, female and combined male and female groups.

		IPSP PkF			IMTP PkF	
	r value	95% CI	Descriptor	*r* value	95% CI	Descriptor
IPSP PkF COM	-	-	-	0.82 **	0.59 - 0.93	*very large*
IPSP PkF M	-	-	-	0.76 *	0.02 - 0.96	*very large*
IPSP PkF F	-	-	-	0.51	-0.06 - 0.83	*large*
IMTP PkF COM	0.82 **	0.59 - 0.93	*very large*	-	-	-
IPSP PkF M	0.76 *	0.02 - 0.96	*very large*	-	-	-
IPSP PkF F	0.51	-0.06 - 0.83	*large*	-	-	-
		IPSP PkFa			IMTP PkFa	
	r value	95% CI	Descriptor	*r* value	95% CI	Descriptor
IPSP PkFa COM	-	-	-	0.43	-0.02 - 0.73	*moderate*
IPSP PkFa M	-	-	-	0.41	-0.50 - 0.89	*moderate*
IPSP PkFa F	-	-	-	0.10	-0.48 - 0.62	*small*
IMTP PkFa COM	0.43	-0.02 - 0.73	*moderate*	-	-	-
IPSP PkFa M	0.41	-0.50 - 0.89	*moderate*	-	-	-
IPSP PkFa F	0.10	-0.48 - 0.62	*small*	-	-	-

IPSP = Isometric Pull from Start Position, IMTP = Isometric Mid-Thigh Pull, PkF = Peak Force, PkFa = Allometrically Scaled Peak Force, COM = Combined Male and Female group, M = Male group, F = Female group. * = $p < 0.05$; ** = $p < 0.01$ denotes statistically significant correlations.

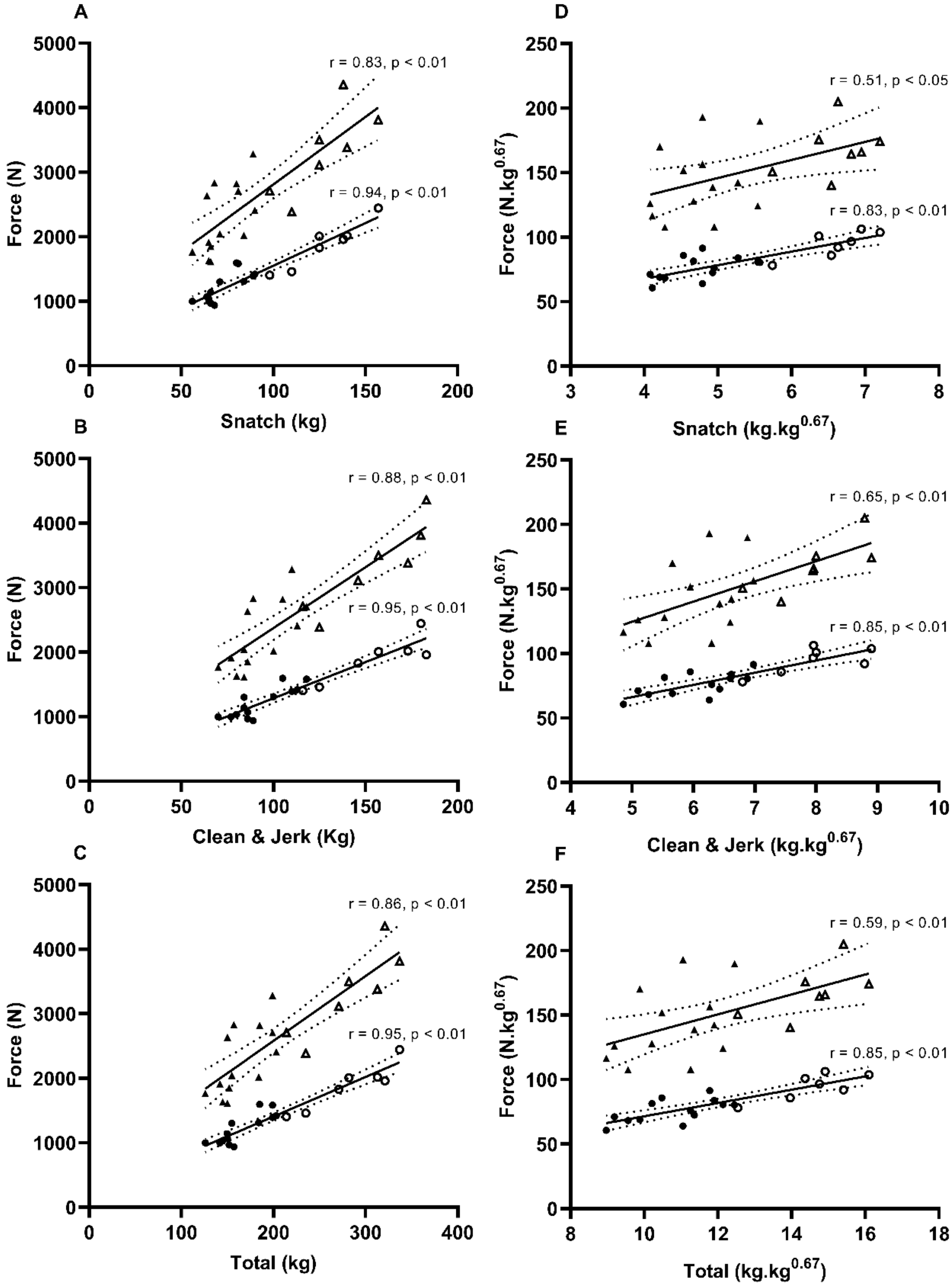

Figure 4: Correlations between absolute and allometrically scaled IPSP, IMTP variables and weightlifting performance measures of the combined male and female group, with 95% Confidence Intervals. (A) Snatch, (B) Clean & Jerk, (C) Total, (D) Allometrically scaled Snatch, (E) Allometrically scaled Clean & Jerk, (F) Allometrically scaled Total. Triangles denote IMTP, circles denote IPSP. Solid symbols denote females, hollow symbols denote males. IPSP = Isometric Pull from Start Position, IMTP = Isometric Mid-Thigh Pull.

A possible explanation for the apparent conflict in research findings might relate to differences in the force-velocity characteristics and intended movement outcomes of the dynamic tasks. It is plausible that these may influence their correlations with isometric tests at varying joint angles or the PkF and RFD variables. For example, in plyometric and ballistic tasks, the intention is to maximise take-off or release velocity at the end of the concentric phase to project one's body mass or an external object into a flight phase (Hubbard, De Mestre, & Scott, 2001; Linthorne, 2001). These tasks may be more limited by the isometric RFD capacity at the position where the maximum force capacity is optimised, as this is where the greatest mechanical advantage occurs and the region of greatest filament cross-bridge cycle transition rate (Fitts, McDonald, & Schluter, 1991). Several investigations have shown that in bilateral triple-extension isometric assessments (isometric squat, isometric mid-thigh pull and isometric leg press) the greatest RFD coincided with the region where maximum force is optimised (knee angles between 120 to 150°) (Bazyler et al., 2015; Bogdanis et al., 2019; Comfort, Jones, McMahon, & Newton, 2015; Palmer, Pineda, & Durham, 2018). This may explain why several investigations report that isometric RFD in shorter muscle lengths exhibits greater correlations with vertical jump performance compared with isometric RFD at longer muscle lengths, and all isometric positions examining PkF (Marcora & Miller, 2000; Rousanoglou et al., 2008). Consequently, for these types of athletic skills, it may be most appropriate to assess isometric RFD within a mechanically specific position to the corresponding dynamic task and at the position where peak force is optimised. On the contrary, in a maximal dynamic strength exercise where the objective is to lift the heaviest weight possible over a relatively constant displacement, the primary limiting factor is the weakest mechanical position across the range of motion. Exercises with linear strength curves such as the back squat, bench press and deadlift, the weakest mechanical position is in the start of the concentric phase (McMaster et al., 2009). It therefore may be necessary to evaluate isometric PkF in a mechanically specific position, however at the position where PkF is the lowest.

The pull phase of the SN and CJ arguably possess characteristics of both maximal dynamic strength and ballistic movements, as the objective is to lift and project a maximal weight high enough to be caught in the overhead or front rack position. However, the sub-phases of the pull, namely the first and second pull exhibit unique positional and temporal force and velocity characteristics (Baumann et al., 1988; Gourgoulis et al., 2009; Harbili, 2012) and function across different end of the muscles force-length curve. The first pull is considered a more strength-oriented phase as it occurs within a comparatively weaker mechanical position and subsequently is a slower movement and requires the lifter to overcome the inertia of the bar (Chavda & Turner, 2020; Garhammer, 1991). Conversely, the second pull is considered a power-oriented movement as it occurs within a stronger mechanical position, is much shorter in duration and exhibits the greatest force, velocity, power, and RFD (Baumann et al., 1988; Gourgoulis et al., 2009). The implementation of both the IPSP and IMTP may therefore be necessary to evaluate the position specific neuromuscular qualities for each of these phases, however this concept warrants further investigation.

In the present investigation, when allometrically scaled to body mass, the IPSP PkFa and IMTP PkFa were poorly correlated with each other across M, F and COM groups, supporting the notion that the maximal force capacity specific to the first and second pull are independent neuromuscular qualities. The evaluation of each of these pull positions may help to identify deficits in the athlete's phase specific strength characteristics and subsequently lead to more directed training prescription. There is also a considerable amount of evidence to suggest that these two positions of the pull may experience specific adaptations in response to muscle length specific training (Bogdanis et al., 2019; Kubo et al., 2006; Noorkõiv, Nosaka, & Blazevich, 2014; Thepaut-Mathieu, Van Hoecke, & Maton, 1988; Ullrich, Kleinöder, & Brüggemann, 2009; Weiss, Fry, Wood, Relyea, & Melton, 2000), however, this is beyond the scope of this investigation.

No differences were observed between M and F groups in correlations between IPSP or IMTP with SN, CJ or TOT, or in correlations between IPSP PkFa or IMTP PkFa with SNa, CJa or TOTa. Furthermore, no differences were observed between M and F groups for the IPSP:IMTP ratio. There was some indication of greater correlations between the two isometric pulling positions with weightlifting performance in the M group compared with the F group and this was observed in both absolute and allometrically scaled values. However, the lack of statistical significance suggests no difference exist between male and female weightlifters in the pulling strength characteristics which relate to weightlifting performance. Therefore, it is evident from our results that male and female weightlifters should train these qualities similarly.

It should be acknowledged that these data are cross-sectional and do not indicate a causal relationship between the IPSP, IMTP and weightlifting performance. However, a recent investigation showed a *large* correlation between the change in IMTP PkF and change in SN, CJ and TOT across two consecutive years in international female weightlifters (r = 0.64 to 0.65) (Joffe & Tallent, 2020) indicating a causal relationship. Based upon the present and previous findings, it is recommendation that future investigations examine the alterations in both isometric pulling positions across an extensive period of specific training to determine the impact of changes in these qualities on weightlifting performance.

In conclusion, these findings suggest that the maximal force capacity in the start position of the first pull has a greater correlation with weightlifting performance measures than maximal force capacity in the start of the second pull. However, when the effects of body mass are controlled for through allometric scaling, these assessments are poorly correlated with each other indicating that each are reflective of independent neuromuscular qualities. Therefore, coaches and practitioners working with competitive weightlifters may consider implementing both the IMTP and IPSP assessments to assess the position-specific neuromuscular characteristics of the pull.

Conflict of Interest

The authors declare no conflict of interest

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Reliability and variability of step mechanics in Rugby Union: A comparison between forwards and backs

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ABSTRACT

The aim of this study was to explore differences in 10 m, 20 m and 40 m sprint times (STs) and initial acceleration kinematic and spatiotemporal step mechanics between Rugby Union (RU) forwards and backs. Nineteen elite male academy RU players (12 forwards; 7 backs; age: 18.0 ± 0.5 years, height: 1.83 ± 0.07 m, mass: 90.3 ± 10.0 kg) were recruited from an English academy club. Subjects completed 3 maximum effort 40 m sprint trials. STs were taken at 10 m, 20 m, and 40 m. Step length (SL), step duration (SD), ground contact time (GCT), flight time, step frequency (SF), step velocity, trunk angle at take-off (T_AT_O), hip flexion at take-off (HF_AT_O), leg extension angle at take-off, shoulder extension angle at take-off (SE_AT_O), and touchdown distance (TD) were collected during the initial acceleration of the sprint via video analysis. Coefficients of variation (CV) were calculated to quantify movement variability. To explore differences independent t-tests were performed with hedges' g effect sizes calculated. CVs for the whole group displayed mixed variability (CV 4.06–18.9%) where HF_AT_O and SE_AT_O were the most varied and SD and SV were the least varied. Backs demonstrated significantly ($p < 0.05$) lower STs, SL, SD, GCT, T_AT_O, TD (moderate–extremely large effect) and significantly higher SFs than forwards. To conclude, differences in spatiotemporal and kinematic step characteristics between forwards and backs were evident, which should be acknowledged when coaching/monitoring sprint technique in RU.

1. Introduction

Rugby union (RU) is an 80–minute, 15 player a side, fast–paced, collision team sport. Players are separated into 2 positional groups, forwards and backs. Forwards are typically heavier than backs and complete more force–based actions such as scrummaging, rucking and mauling where backs are usually more athletic in stature and complete higher velocity-based tasks including change of direction (CoD) and sprinting to evade opponents (Deutsch, Kearney, & Rehrer, 2007).

Sprinting is important for all positions in RU, particularly over short distances (Barr, Sheppard, Gabbett, & Newton, 2014) to gain territorial advantage and penetrate defensive lines. During match time motion analysis players have been reported to complete sprints in bursts between 0–40 m (Sayers, 2000). Therefore, the ability to accelerate is an important factor (Bangsbo, Norregaard, & Thorsoe, 1991) and thus developing sprinting speed in RU seems to be of fundamental importance.

In research, sprinting gait is often divided into sub–phases consisting of stance phase, terminal swing, mid swing, initial swing, and touchdown (Dicharry, 2010). In order to achieve effective sprint gait kinematics and kinetics (McFarlane, 1984), coaches tend to cue athletes to accelerate with: a forward leant torso angle, big arm drive, long stride length with full triple extension of the rear leg, ball of the foot plant and dorsiflexion as this has been found to be the most efficient way to accelerate according to research (Hoffman & Graham, 2011). However, although this is deemed the fastest way to accelerate based on 'the fastest of all-time athletes' (Wild, Bezodis, North, & Bezodis, 2018) there are many demands that can interfere with the

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fundamental mechanics of sprinting alone in RU such as contact collisions (Bradshaw, Maulder, & Keogh, 2007; Coh, Jost, Skof, Tomazin, & Dolenec, 1998; Dick, 1989; Hay, 1993; Jeffreys & Goodwin, 2016; Ryan & Harrison, 2003; Seagrave et al., 2009). Alongside this, due to the differing within position demands and anthropometrics in RU, there are likely intra-athlete variability between forwards and backs. Forwards are likely to show varying sprint mechanics to not only the traditional track and field sprinters, but also their co-players, backs (and vice versa). However, research is lacking in this area.

Current research has shown that maximal velocity is usually attained between 65–75 m in track sprinters (Mackala & Mero, 2013) however research shows differently within RU. Barr et al. (2014) found that RU players attain maximum velocity (MV) between 30–40 m, due to player adaptations to the game. Wingers were found to produce the greatest MV at 39 m where some positions produced MV as early as 33 m showing intra-athlete variability in MV attainment. (Nagahara, Takai, Kanehisa, & Fukunaga, 2018). Whilst this is the case, due to the constant intercepting actions during sprint burst in RU, players will rarely sprint for longer than 30 m. Therefore, MV is very rarely met, highlighting the importance of acceleration in RU (Cross et al., 2015).

According to the deterministic model the key kinematic parameters for acceleration include: step velocity (SV), step frequency (SF), ground contact time (GCT), flight time (FT) and step length (SL) (Fletcher, 2009). Such variables have been deemed to be key due to the formula: Running speed = SL x SF (Fletcher, 2009), where an enhancement in variables such as GCT and FT can further improve SL and/or SF thus overall sprint performance (Lockie, Murphy, Schultz, Jeffriess, & Callaghan, 2013). Lockie et al. (2013) found SL to correlate to initial accelerative sprint performance of 10 m sprints in team sport athletes (0–5 m: $r = 0.502$, $p \leq 0.011$). Lockie et al. found that FT showed the highest correlation to 0-5 m acceleration performance ($r = 0.522$, $p \leq 0.007$). Although, authors failed to present the magnitude of the differences (i.e., effect size) or reliability measures (i.e., intraclass correlation coefficient) for the testing variables. But interestingly, upon calculating the CV% for SL, GCT and FT it was evident that FT was the least varied (SL = 9.15%; SF = 12.9%; GCT = 9.69%; FT = 6.53%). Due to the high correlation and low variability of FT it could be suggested that a longer FT may produce ideal step mechanics for acceleration performance. However, the testing sample included subjects from RU, rugby league, Australian rules football, soccer, and field hockey (Lockie et al., 2013). This range of sports is likely to have created large variation in results meaning calculated CV% may be inaccurate. The heterogeneous sample used, also does not represent specific RU sprinting characteristics so it is likely that differences may not be practically meaningful and may not show relevant findings to any specific sport.

Despite the importance of sprinting in RU, limited studies have assessed the reliability and variability of step mechanics between forwards and backs. The only study to have researched this area is Wild et al. (2018). Wild et al. (2018) compared mechanics between forwards and backs and found differing touchdown and toe off positions during the sprinting action between the two positional groups. Backs had a more posterior touchdown and toe off position (i.e., greater leg extension to maximise propulsion) compared to forwards. Backs also displayed shorter GCTs producing large effect size differences across steps 2 and 3 of sprint performances compared to forwards (Wild et al., 2018). In contrast, only trivial and small effect size differences were shown between contact lengths (horizontal distance the centre of mass travelled during stance). Touchdown placement for RU players relative to centre of mass has been shown to be further forward compared to track and field athletes, showing ‘very large’ effect sizes (sprinters vs forwards) (Wild et al., 2018). Such effect size differences have been suggested to be due to the forward orientation of the ground reaction force vector. Anthropometrical factors like range of motion at the hip, rate of force development and body mass are likely reasons for these variances (Wild et al., 2018). Due to forwards being heavier than backs, forwards have to produce larger forces to overcome inertia suggesting reason for the greater touchdown distance (TD). Intraclass correlation coefficient (ICC) and confidence limits were almost perfect between first and second digitising periods of the study (ICC > 0.90; Confidence Limits 0.85-0.99) (Wild et al., 2018). However, Wild et al. (2018) failed to present reliability and variability measures between forwards and backs for each of the variables tested in the study.

There is limited research in the background of STs and acceleration kinematics and spatiotemporal step mechanics in RU players. Previous research has assessed initial step mechanics in track and field athletes but there is limited research assessing the reliability and intra-athlete variability of step mechanics in RU. Evaluating sprint technique in the field is time consuming and requires the need for expert training to use digitisation techniques. This has potentially led to neglecting the evaluation of spatiotemporal step mechanics in team sports. Thus, there is a need to develop a practitioner friendly approach to measure spatiotemporal mechanics for team sport strength and conditioning coaches to use in practice. Furthermore, to the authors’ knowledge no study has evaluated the variability of sprint times or step mechanics between RU positions. Therefore, the aim of this study is to explore differences in 10 m, 20 m and 40 m STs and initial acceleration kinematic and spatiotemporal step mechanics between RU forwards and backs. To achieve this aim, the study has the following objectives; 1) quantify the variability of SL, step duration (SD), GCT, FT, SF, SV, trunk angle at take-off (T_AT_O), hip flexion angle at take-off (HF_AT_O), leg extension angle at take-off (LE_AT_O), shoulder extension angle at take-off angle at take-off (SE_AT_O), TD in forward and backs; and 2) explore differences between forwards and backs in the abovementioned technique variables. It was hypothesised that forwards would have more variability (CV) compared to backs across all variables. In particular backs would produce more varied STs (<CV) than forwards. In terms of step mechanics, it was hypothesised that backs would have a higher SF with a shorter SL compared to forwards.

2. Methods

2.1. Participants

Nineteen semi-professional elite male academy RU players (forwards, n = 12; age: 18.0 ± 0.5 years, height: 1.84 ± 0.08 m, mass: 92.8 ± 10.5 kg; backs, n = 7; age: 18.0 ± 0.5 years, height:

1.82 ± 0.05 m, mass: 86.0 ± 7.91 kg) were recruited from a professional English academy to take part in the study. A minimum of 14 (n = 7 each group) participants was determined from an *a priori* power analysis using G*Power (Version 3.1.9.2, University of Dusseldorf, Germany) (Dos'Santos, McBurnie, Thomas, Comfort, & Jones, 2020). This was based upon a previously reported Cohen's *d* effect size of 1.69 (step 3 contact time) (Wild et al., 2018), a power of 0.8, and type 1 error or alpha level 0.05. All subjects wore studded rugby boots and regularly completed a two and a half hour training session three times a week. Each session includes: rugby training, strength and conditioning training, plyometric training and sprint training. Subjects were currently in-season training and were in a speed-strength meso-cycle. Ethical approval was obtained from the University of Salford ethics board, and all subjects provided written informed consent to participate in the study. All subjects completed a physical activity readiness questionnaire to check eligibility and ensure safety. At the time of the study all subjects were injury free and were familiar with sprint training/testing as part of their rugby programme across 10–100 m.

2.2. Apparatus and Task

Testing took place in a single session at one site. The test was selected as it has been shown to be highly reliable (Darrall-Jones, Jones, Roe, & Till, 2016). In addition, the 40 m sprint is the maximum sprint distance likely to be covered during RU (Sayers, 2000). Subjects completed 3 maximal effort trials on a synthetic 3G AstroTurf surface with STs taken at 10 m, 20 m and 40 m using a single beam photocell timing gate system. A video camera was placed in the acceleration portion down the track in order to evaluate early acceleration sprinting technique similar to previous research (Wild et al., 2018). Several kinematic parameters were determined from video analysis and within session reliability and variation was quantified using ICCs with 95 % Confidence intervals (CI) and CV for the group as a whole and positional sub-group (forwards n = 12, backs n = 7). Furthermore, positional group comparisons were made for all abovementioned variables and Hedges' *g* effect sizes calculated.

2.3. Procedures

The data collection used an experimental quantitative approach (between subjects, cross sectional design) to assess the reliability and variability of the 10 m ST, 20 m ST and 40 m. The study also assessed SL, SD, GCT, FT, SF, SV, T_AT_O, HF_AT_O, LE_AT_O, SE_AT_O, TD of the acceleration (0–5 m) portion of 40 m maximal effort sprint. Subjects undertook a standardized warm up consisting of dynamic stretching and three sub maximal 40 m running efforts (50% effort; 75% effort; 95% + effort) from a standing start in line with successful previous research (Dos'Santos, Thomas, Jones, & Comfort, 2017). Testing took place on a 3G AstroTurf pitch. Using a measuring tape, a 40 m track was marked out in a straight line along the AstroTurf. A Panasonic Lumix DMC-FZ200 camera (Panasonic corporation, Kadoma, OSA, JP) sampling at 100 Hz set on a manual focus setting was placed at 3 m down the track, 5 m away from the track perpendicular to the sagittal plane of motion of the subject during the trial. The resolution of the camera was set to 1280 x 720p. This enabled evaluation of initial acceleration steps (first 3 steps) of each trial. The camera was placed on a rigid tripod 0.98 m off the floor with 1 pair of Draper flood lights (WL28, Draper, UT, USA) (1500 watts) on a 3 m tall tripod. The flood lights were placed 5 m down the track, 45° from the plane of motion to enhance lighting for the field of view of the camera in the acceleration phase. The field of view of the camera was 7 m where measurements were only taken in the central 5 m of the field of view in order to reduce parallax error. A 1.22 m calibration frame was set directly in front of the camera frame in the centre of the track. Brower photocell timing gates (BRO001; Brower, Draper, UT, USA) were placed at 0 m, 10 m, 20 m and 40 m along the track, timing to the nearest 0.001 s (Figure 1). Timing gates were set up to approximately hip height

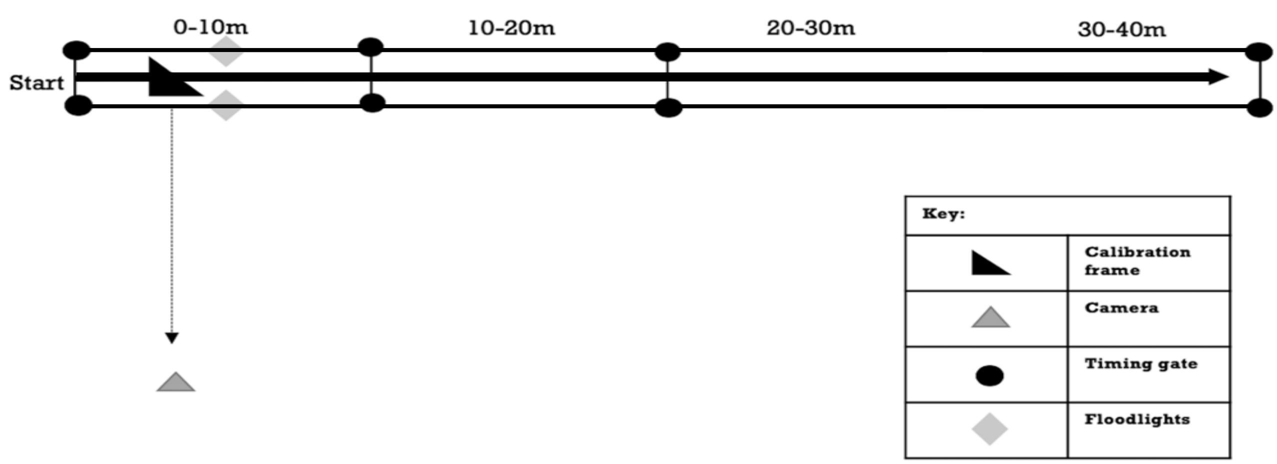

Figure 1: Diagram of 40 m sprint testing set up

Table 1: Acquisition/definition of step mechanic variables (Hunter et al., 2004; Seagrave et al., 2009)

Step mechanics	**Process of acquisition/definition**
Step length (m)	Toe to toe horizontal distance between consecutive foot contacts
Step duration (s)	Number of frames from take-off to take-off of consecutive steps × 1/100
Ground contact time (s)	Number of frames from touchdown to take-off of one-foot contact × 1/100
Flight time (s)	Number of frames from take-off to touchdown of during one step × 1/100
Step frequency	1/ step duration
Step velocity (m/s)	Step length × step frequency
Trunk Angle at Take-Off (°)	Angle of trunk relative to the vertical at take-0.508-. Where a lower trunk would be a more upright and vertical posture.
Leg Extension Angle at Take-Off (°)	Angle of rear leg at full extension relative to vertical at take-off.
Hip Flexion Angle at Take-Off (°)	Angle of forward leg relative to centre of knee to the centre of hip joint during take-off of swing leg. A lower hip flexion angle would have greater knee lift.
Shoulder Extension Angle at Take-Off (°)	Angle formed between upper arm and trunk at take-off to TD (m) (horizontal distance of toe to centre of hip of support leg at touchdown). Where a greater shoulder extension angle would result in a greater backward arm drive
Touchdown distance (m)	Horizontal distance of toe to centre of hip of support leg at touchdown. A foot landing further forwards relative to the centre of hip of support leg would result in a greater touchdown distance.

of each subject to ensure the lower torso broke the beam to ensure reliable results in line with previous research (Yeadon, Kato, & Kerwin, 1999). Subjects started 0.5 m behind the first timing gate in a 2-point staggered athletic start and were told not to rock back in order to prevent the timing beam from breaking prematurely (Woolford, Polgaze, Rowsell, & Spencer, 2013). Each subject then completed 3 maximal effort trials of the 40 m sprint. Subjects were signaled to start with synchronization of the camera recording for each trial to *"run as fast as possible and to not decelerate until they passed the final timing gate"* (Woolford et al., 2013). Subjects were encouraged throughout the trial and given rest periods of 3–4 minutes between trials (Wild et al., 2018). Split times were recorded for each trial for each subject. A step was defined as *one consecutive movement of right foot contact to left foot contact* similar to that used by Wild et al. (2018). The point of touchdown was identified as *the first frame the foot was visibly in contact with the ground* and toe off was identified as *the first frame the foot had visibly left the ground* (Wild et al., 2018).

Times were taken and averaged in a Microsoft excel spreadsheet (Microsoft Corp., Redmond, WA, USA) for each subject for further data and statistical analysis. Videos were imported into Quintic Biomechanics software (v31, Solihull, UK) and calibrated ready for further analysis. Using the 'angle drawing', 'shapes' and 'marker' functions in Quintic, several variables were determined from the first three consecutive steps (these values were then averaged across steps then reported) with the aim to allow these variables to be easily measured by coaches using video analysis. Definitions for each variable acquired from trials are presented in Table 1. Technique variables were determined for the first 3 steps of each trial and then averaged across the three steps. The data was then separated into two groups, forwards and backs.

2.4 Statistical Approach

Test-retest intra-rater reliability of manual digitization for all step mechanics were determined using ICC (ICC 3,1) with 95 % CI (Shrout & Fleiss, 1979; Wild et al., 2018). The data of 10 participants, of whom were selected at random from the testing sample was digitized on two separate occasions 2 weeks apart similar to work done by Wild et al. (2018). All statistical analysis was conducted in SPSS for windows (Version 23; SPSS Inc., Chicago, IL, USA). ICCs with 95% CI were used to test rank order consistency between trials (two-way mixed effects, average measures, absolute agreement) for the whole group and positional sub-groups. ICCs were interpreted as poor reliability (< 0.5), moderate reliability (0.5-0.75), good reliability (0.76-0.9) and excellent reliability (> 0.9) in line with Koo and Li (2016) where ICC ≥ 0.7 was deemed acceptable (Baumgartner & Chung, 2001). Intra-rater reliability with 95% CI were calculated using (two-way random effects, average measures, absolute agreement).

Percentage within subject CV was calculated to determine the variability across 3 trials for each variable using SD/mean x 100. Average CV and 95% CIs were calculated and reported where acceptable CV was <15% (Baumgartner & Chung, 2001). Normality was inspected using a Shapiro-Wilks test. Normality ($p > 0.05$) was confirmed for 10 m, 20 m, 40 m, SL, SV, T_AT_O, LE_AT_O, HF_AT_O and SE_AT_O; thus, to explore differences between positional groups a parametric independent samples T-Test was performed. A Levene's test was used to test the assumption of equality of variances, with degrees of freedom adjusted for 'variances not assumed' for violations of this assumption. SD, GCT, FT, SF and TD were not normally distributed ($p < 0.05$); thus, a Mann-Whitney U test was used to explore positional differences. Effect sizes were determined and corrected using Hedges' *g* due to uneven sample sizes, with values interpreted as follows: trivial (≤ 0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99) and very large (2.0–4.0) extremely large ≥ 4.0 (Hopkins, 2002).

3. Results

ICCs between the first and second digitizing occasions indicated excellent intra-rater reliability for all step characteristics (ICC = 0.993 – 1.00, 95% CI = 0.972 – 1.00). Mixed reliability and variability (ICC=0.508–0.892, moderate-good; CV = 4.06–18.9%) was found for all step characteristics in grouped data. CVs for forwards and backs individually are presented in Table 2. Step mechanics demonstrated varied results (forwards ICC = 0.023–0.847, poor-good, CV ≤ 11.02%; backs ICC = -0.003–0.643, poor-moderate; CV = 2.73–9.91%). Backs demonstrated significantly ($p < 0.05$) lower STs, SL, SD, GCT, T_AT_O, TD and SE_AT_O (moderate–extremely large effect) compared to forwards (Table 2 and Figures 2 and 3). Backs also demonstrated significantly higher ($p < 0.05$) SF (small effect) compared to forwards (Table 2 and Figure 3).

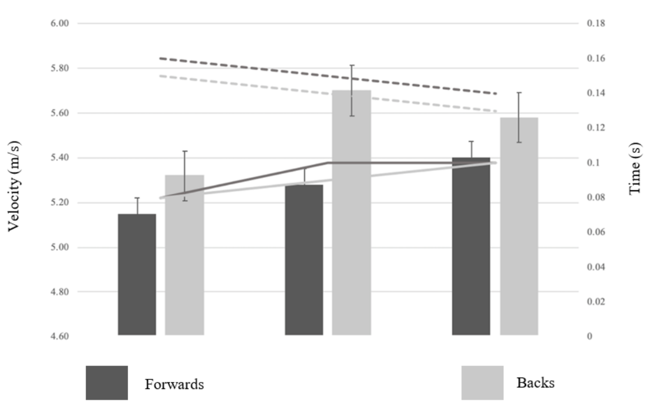

Figure 2: Comparison between forwards and backs for velocity, ground contact time and flight time over the first three steps of sprint performance. Bar chart = Velocity (m/s); Solid lines = Flight time (s); Dashed lines = Ground contact time (s)

4. Discussion

The aim of this study was to explore differences in 10 m, 20 m and 40 m STs and initial acceleration kinematic and spatiotemporal step mechanics between RU forwards and backs. The results of forwards alone and backs alone showed that both positional groups produced acceptable CVs on all occasions. SL showed the least variability (CV = 3.89%) in backs and SD showed the least variability in forwards (CV = 1.37%). The hypothesis was partially accepted as backs displayed less varied STs compared to forwards (ST forwards CV ≤ 4.83%, ST backs CV ≤ 4.01%). Backs displayed higher SF with shorter SL compared to forwards which also accepts the hypothesis. Although this was evident, forwards displayed less varied step mechanics in a higher number of variables compared to backs, rejecting the hypothesis.

Joint angle variables HF_AT_O and SE_AT_O displayed the greatest CV scores for both forwards and backs but were still acceptable. Bradshaw et al. (2007) agreed with our findings and found greater variability involving the measurement of joint angles. Findings showed that T_AT_O displayed the greatest CV (CV = 8.31%). Although Bradshaws CV for T_AT_O was acceptable, it was still Bradshaws' most varied variable. This suggests joint angle variables are problematic variables to obtain consistent data from and stricter guidelines should be followed to enhance the likelihood of consistency. However, in Bradshaw's study subjects were male track and field sprinters therefore direct comparisons cannot be made.

On the other hand, the high variability exhibited for HF_AT_O and SE_AT_O could be due to the need for a higher degree of 'flexibility' in shoulders and hips in order to execute these variables efficiently. Both SE_AT_O (arm drive) and HF_AT_O (knee lift) vary from sprint to sprint in order to adapt to differing game circumstances on field, e.g., pushing off an opponent or acceleration into different directions. Thus, the adaption of co-ordination within these variables during a given situation on field shows another potential area for variability.

TD displayed a large effect where backs produced significantly shorter TDs (g =1.53, $p < 0.001$) substantiating previous findings (Wild et al., 2018). Backs also had increased T_AT_O (large effect) and arm drive/SE_AT_O (small effect) compared to forwards. The combination of an increased trunk lean (T_AT_O), decreased TD and increased arm drive (SE_AT_O) in backs theoretically may enable players to increase horizontal force production which in turn increases horizontal velocity, as the centre of mass is ahead of the base of support during the majority of the ground contact phase reducing initial braking impulse leading to a great net horizontal impulse. The adoption of this more efficient running technique in backs confirms conclusions by Wild et al. (2018). Sayers (2000) also found similar results in field sport players, demonstrating smaller arm actions/reduced SE_AT_O resulted in a detriment to the biomechanical characteristics required for good running technique.

It was clear that backs had faster absolute STs (CV ≤ 4.01%) showing moderate differences. This was also confirmed when looking at individual steps as backs displayed higher SVs at all three steps (Figure 2). Forwards in the current study had higher average SLs where backs had greater average SFs. When comparing individual steps for SF it was evident that backs had a

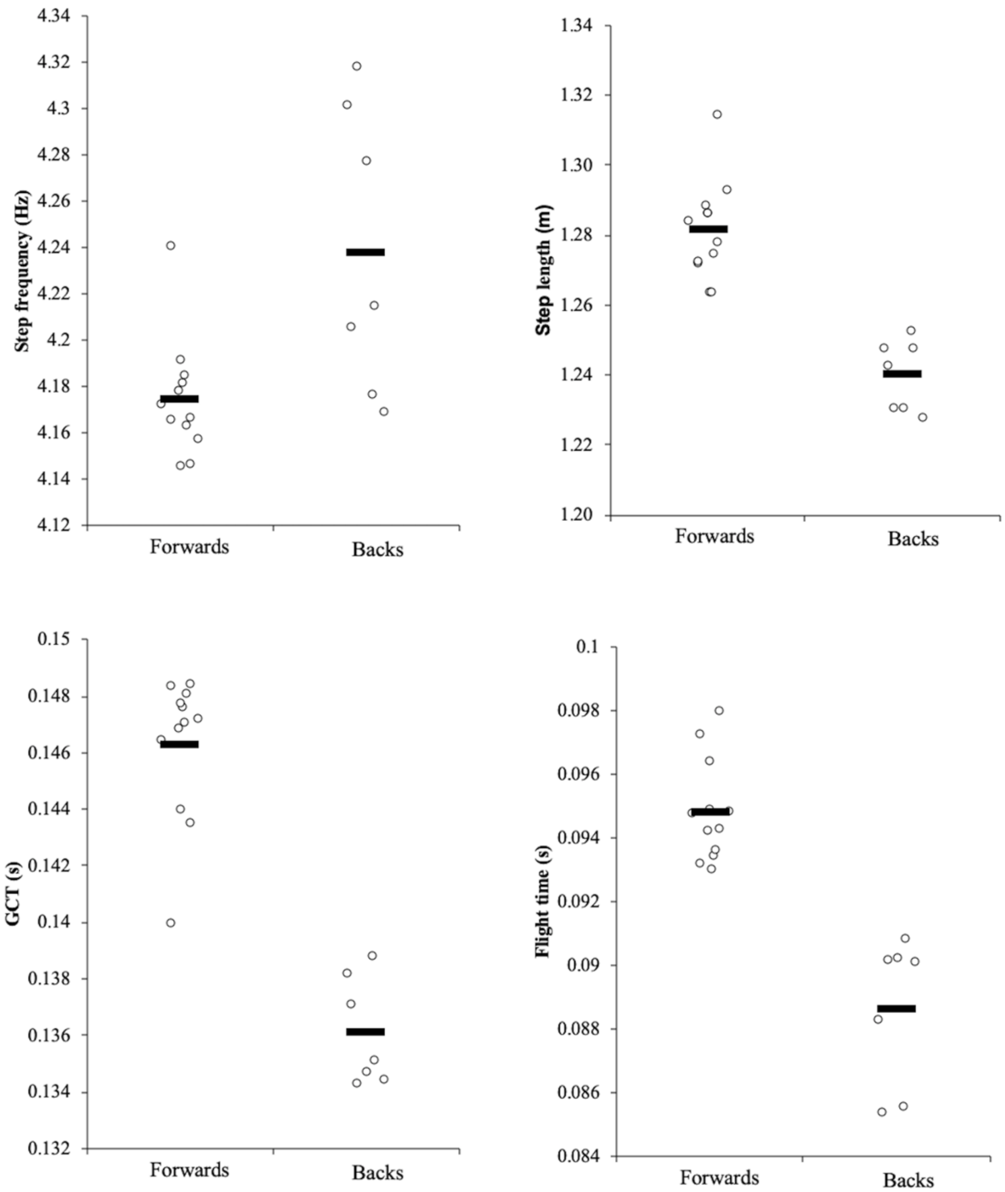

Figure 3: Dot Plots for step frequency, step length, ground contact time (average of first 3 steps) and flight time of forwards versus backs

much higher SF for steps 1, 2 and 3 compared to forwards confirming average results. Although less, on average backs also showed less varied SLs (g = 1.00) compared to forwards displaying a more consistent running style. Our SL findings agree with findings by La Monica et al. (2016) who also found forwards had longer SLs and backs had higher SFs. Due to the fastest subjects in current the study (backs) displaying less varied SLs and (g = 1.00) and higher SFs our results suggest that for the fastest SV subjects should display higher SFs. Previous research has found similar, but stated that for enhanced results, the highest SF that can be maintained with the highest possible SL would result in superior results (Hunter, Marshall, & McNair, 2004). CV for isolated forwards and backs SV, SL and SF in the current study were acceptable (CV ≤ 4.42%) on all occasions however it still cannot be concluded that a high SF with a lower SL is optimal as only small-moderate differences were evident and correlations between SV-SF and SV-SL were not measured.

Results from the current study also suggest that taller/longer limbed subjects find it much more challenging to reach higher SFs. In contrast to this, although La Monica et al. (2016) agreed with our findings, forwards and backs in La Monica's study were both of the same average height thus suggesting height does not explain differences. Although such findings were evident, our results agree with findings by Wild et al. (2018) who also found taller subjects had lower SF (forwards vs track and field athletes). But

Table 2: Descriptive statistics, reliability measures and effect sizes for average of first three steps for 40 m sprint

Step Mechanics	*p*	Forwards Mean and ± SD	CV %	95 % LB	95 % UB	Backs Mean and ± SD	CV %	95 % LB	95 % UB	*g*	± 95 % CI
10 m sprint time (s)	0.044	1.90 ± 0.09	4.83	2.90	6.76	1.83 ± 0.07	4.01	1.91	6.11	0.74	0.96
20 m sprint time (s)	0.017	3.20 ± 0.13	4.01	2.40	5.61	3.08 ± 0.08	2.73	1.30	4.17	1.08	0.99
40 m sprint time (s)	0.045	5.58 ± 0.24	4.30	2.58	6.01	5.39 ± 0.15	2.77	1.32	4.22	0.91	0.98
Step length (m)	<0.001	1.28 ± 0.03	2.25	1.35	3.15	1.24 ± 0.05	3.89	1.85	5.93	1.00	0.98
Step duration (s)	<0.001	0.24 ± 0.00	1.37	0.82	1.92	0.22 ± 0.01	3.98	1.90	6.07	2.32	1.19
Ground Contact time (s)	0.001	0.15 ± 0.00	2.41	1.45	3.39	0.14 ± 0.01	5.28	2.51	8.04	1.72	1.08
Flight time (s)	0.161	0.09 ± 0.00	2.25	1.35	3.16	0.09 ± 0.00	4.40	2.10	6.71	1.88	1.11
Step Frequency (Hz)	0.010	4.17 ± 0.06	1.44	0.87	2.02	4.24 ± 0.19	4.42	2.10	6.73	-0.43	0.94
Step Velocity (m/s)	0.068	5.34 ± 0.08	1.48	0.89	2.07	5.39 ± 0.23	4.18	1.99	6.37	-0.28	0.94
Trunk angle at take-off (°)	<0.001	34 ± 2	4.94	2.96	6.92	31 ± 2	7.41	3.53	11.30	1.40	1.03
Leg extension angle at take-off (°)	0.163	43 ± 1	2.27	1.36	3.18	42 ± 2	4.29	2.04	6.53	0.21	0.93
Hip flexion angle at take-off (°)	0.448	27 ± 3	11.02	6.61	15.44	28 ± 3	9.91	4.72	15.10	-0.12	0.93
Shoulder angle extension at take-off (°)	0.058	49 ± 3	6.58	3.95	9.21	50 ± 4	7.80	3.71	11.88	-0.42	0.94
Touch down distance (m)	<0.001	0.27 ± 0.02	6.21	3.73	8.69	0.24 ± 0.02	7.46	3.55	11.37	1.53	1.05

Trivial ES	Small ES	Moderate ES	Large ES	Very Large ES	Extremely Large ES

Note: SD = Standard deviation; CV % = Coefficient of variation; 95 % CI LB = 95 % Confidence interval lower bound; 95 % CI UB = 95 % Confidence interval upper bound similar to La Monica et al., Wild et al. also found that backs vs track and field athletes were of similar height (± 0.01 m) but backs produced higher SF than track and field athletes (small effect). This was likely due to the nature the track and field athletes sport being based completely around running alone. The majority of a track and field athletes training is built solely around linear step mechanics and does not involve skills such as CoD or passing. Track and field athletes also have a greater focus on developing and maintaining MV thus signifying sprinters were more familiar and developed with the action of sprinting.

A large effect was found for GCT and FT (Table 2 and Figure 2). This supports findings by Barr et al. (2014) who found that faster RU players had shorter GCTs. Shorter GCTs are important to establish higher SF, thus explaining the lower GCTs and higher SF in backs compared to forwards, who were more SL dependent (Figure 2 and 3). When comparing individual steps, it was clear that backs had shorter GCT and longer FT for each of the three steps confirming the accuracy of average results (Figure 2 and 3). The fact that there were no significant differences observed between positional groups for LE_AT_o and HF_AT_o suggests there are no differences in the leg extension angle in order to maximise propulsion force and amount of knee lift during sprinting.

When assessing the usefulness of the 40 m sprint as a testing battery, it may not be deemed as the best method. Backs cover higher sprint distances than forwards during game play (Cahill, Lamb, Worsfold, Headey, & Murray, 2013) and therefore it may not be appropriate for forwards to carry out 40 m sprints as part of their training programme. Shorter sprints may be a better replacement allowing a better transfer to RU. The high effect size differences in step mechanics between positions also suggest it may be difficult to teach the same technique. Differences in anthropometrics propose it may be beneficial if positions had different sprinting technical models. Practitioners should take this into consideration.

In conclusion, acceptable CVs can be derived from all variables for both forwards and backs (Baumgartner & Chung, 2001). HF_AT_O and SE_AT_O displayed the lowest CVs for both groups. Forwards had lower CVs in a higher number of variables than backs, rejecting the hypothesis. The hypothesis was accepted in terms of step mechanics, where backs displayed higher SF, shorter SL and faster STs than forwards.

Backs had faster absolute GCT and it was evident that forwards were more SL dependent thus, the development of separate technical models for positions individually may improve coaching prescription to enhance sprint performance, but future research is needed in this area. An increase in SF with a greater LE_AT_O (Hunter et al., 2004) should be adhered to for faster SVs. Increased T_AT_O, SE_AT_O and decreased TD should also be a focus for practitioners. But it should be noted that shorter sprints for forwards may allow a better transfer to RU. Overall, due to SL and SD having lower variability suggests that these variables could be used to monitor the development of step mechanics in periodized training programs. Future research should also consider the comparison step mechanics of specific steps rather than an average of steps when analyzing sprint performance for even more accurate results.

Assessing spatiotemporal kinematics in RU players may be a tool to monitor sprint performance. Differences in kinematics and spatiotemporal characteristics were evident between forwards and backs which may indicate that there will be position specific technical models. Therefore, from a practical standpoint coaches may want to separate players into positions when carrying out sprint training in order to address differing weaknesses. Coaches should also consider having forwards carry out shorter sprints as part of their training programme. Coaching RU players to have an optimal combination of a higher SF, shorter SD and longer SL may display enhancements in step mechanics. Coaches may consider using external cues to achieve desired outcomes, as it has been found, external cues allow subjects to better responding to instructions (better quality of movement and higher successful frequency of responses to instructions) (Wulf, McNevin, & Shea, 2001). Cues such as "the floor is lava" in order to improve SF whilst encouraging players to "maximally drive/push the floor away" to achieve longer SLs (Wulf, McNevin, & Shea, 2001). Coaches may also consider implementing fast stretch-shortening cycle plyometrics such as pogos, rope jumps, travelling pogos or hurdle jumps with a focus on minimizing GCT and maximizing jump height, therefore maximizing SF and SL and exhibiting greater RU sprint performances.

Conflict of Interest

The authors declare no conflict of interests.

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The reliability of isometric neck strength assessments in trained individuals

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ABSTRACT

Cervical muscle strength has been identified as a modifiable risk factor for concussion and cervical spine injury. At present, there is a dearth of research investigating reliable methods of measuring neck strength which are: suitable for implementation into a sporting environment (for example: a strength and conditioning suite, training facility and match facility), accessible to athletes who play contact sport or are at risk of suffering concussion, and which can be used for regular testing, monitoring and evaluation of groups of athletes. The aim of this investigation was to examine the reliability of a method of measuring isometric neck strength using a portable dynamometer (PD) mounted on a custom-built bracket, appropriate for use in an applied sport and exercise environment. Measurements were conducted in flexion, right-side flexion, extension, and left-side flexion using a PD and custom-built rack. Fourteen participants had their isometric neck strength measured in two sessions, 24 h apart at a university strength and conditioning gym. Participants completed three isometric contractions in each of the four directions with 30 s between each repetition. Participants peak isometric neck strength measurements and time to peak force measurements were used for data analysis. The height of the PD and order of pushing positions remained constant between both sessions. This method demonstrated strong relative and absolute reproducibility for measuring peak isometric force (PF) of the neck musculature in all directions (PF ICC ranged between 0.78 - 0.94 across all directions. PF r ranged between 0.81 - 0.92 across all directions. PF CV% ranged between 8.86 - 10.43 in all directions). However, findings show poor relative reproducibility for the measurement of time to peak isometric force (TPF). Systematic bias was small and the difference between the trials for PF and TPF were not significant ($p > 0.05$ in all directions).

1. Introduction

Sports related concussion (SRC) has received growing attention in both the sports medicine community, as well as the media due to the increase in prevalence in both youth and senior sport (Mannix et al., 2016). For instance, in the 2017/2018 English Premiership Rugby season, concussion was the most reported match injury (17.9 per 1000 hours) for the seventh consecutive season, contributing 20% of all match injuries (England Professional Rugby Injury Surveillance Project Steering Group, 2018). Concussion in sport occurs as a result of sudden impacts and collisions to the head or body, causing the brain to move and subsequently bump against the skull (Weed, 1935). The force of the brain being pushed against the side of the skull can damage blood vessels, nerve fibres, cause bruising and disrupt normal brain function, thus resulting in a mild traumatic brain injury (TBI) called concussion (Cosgrave & Williams, 2019; Pearce et al., 2018; Weed, 1935). The 2019 American Medical Society for Sport Science (AMSSM) (Harmon et al., 2019) concussion position statement highlighted that prevention of cervical spine injuries and concussion is not possible. However, assessment, monitoring and management of such injuries, including preventative measures to decrease the incidence and severity, are valuable when improving the safety of contact sports (Harmon et al., 2019).

Research into TBI in contact sport has led to an interest in measuring, monitoring, and training neck strength (Almosnino et al., 2010; Collins et al., 2014; Eckner et al., 2014; Harmon et al.,

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2019). Current research suggests that low neck strength is a potential modifiable risk factor that may contribute to elevated concussion risk, due to the greater linear and angular head displacements, velocities and accelerations which occur post impact (Eckner et al., 2014). It has been found that stronger muscles are capable of absorbing higher forces due to greater tensile stiffness and the ability to produce torque more rapidly than weaker muscles, which intern attenuates the heads response to impact (Conley et al., 1997; Dempsey et al., 2015; Eckner et al., 2014). This was demonstrated by Viano et al. (2007) who found stiffer necks reduced head displacement, acceleration and velocity and reduced concussion incidences in footballers; and further by Mihalik et al., (2010) who proposed that the ability to anticipate a collision in Rugby allowed for greater activation of cervical muscle structure and mitigated the severity of the impact, by having greater neck stiffness to absorb the external force applied to the head and neck. A growing body of research suggests that measuring, monitoring, and improving neck strength through strength training could have a positive impact on mitigating the severity and occurrence of such injuries (Collins et al., 2014; Conley et al., 1997; Dempsey et al., 2015).

Isokinetic dynamometry is considered to be the gold standard for measuring isometric limb strength (Dvir & Prushansky, 2008), however to date, there is no agreement on what is considered to be the gold standard for measuring isometric neck strength either in field-based or clinical settings, this is due to the range of custom-built equipment which is currently used to assess isometric neck strength. Despite the range of equipment, clinical studies have shown that measuring isometric neck strength in four directions: flexion, right-side flexion, extension, and left-side flexion, to be reliable and valid, however, the equipment used was laboratory based and tailored towards collecting clinical data in both symptomatic and asymptomatic participants (Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999). A number of studies have been successful in demonstrating clinical reliability, validity, and relevance (Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Prushansky et al., 2005), yet there has been little attention directed towards ensuring there are reliable methods available which are suitable for implementation in applied sport environment, such as gyms, sports grounds and changing rooms.

Existing literature shows a range of different equipment and protocols have been used to measure isometric neck strength (Bohannon, 1993; Chiu & Lo, 2002; Collins et al., 2014; Conley et al., 1997; Dempsey et al., 2015; Dvir & Prushansky, 2008; Jordan et al., 1999; Krause et al., 2019; Mihalik et al., 2010; Olivier & du Toit, 2008; Prushansky et al., 2005; Versteegh et al., 2015; Viano et al., 2007). The widely reported methods used to measure isometric neck strength reliably are: Handheld dynamometry (HHD) using a portable dynamometer (PD), fixed frame dynamometry (FFD), manual muscle testing (MMT) and isokinetic measurements. HHD, FFD, MMT and isokinetic measurements are commonly used for assessment and rehabilitation purposes. Within the existing body of research, each method of measuring cervical neck strength has been thoroughly investigated (Bohannon, 1993; Chiu & Lo, 2002; Collins et al., 2014; Conley et al., 1997; Dempsey et al., 2015; Dvir & Prushansky, 2008; Jordan et al., 1999; Krause et al., 2019; Mihalik et al., 2010; Olivier & du Toit, 2008; Prushansky et al., 2005; Versteegh et al., 2015; Viano et al., 2007). However, the current body of research has not investigated the application of aforementioned methods' in an applied sport environment as a potential preventative measure against TBI in contact sport. This is most likely to be because of the inaccessible, time consuming nature of current equipment, meaning it is not feasible to carry out measurements in applied settings.

Therefore, the method devised here, aims to address the barriers and difficulties which arise when implementing the current methods of measuring neck strength into an applied sport and exercise environment. For example, existing methods utilising FFD and isokinetic measurements are largely laboratory based, requiring specialised equipment such as computerised load cells and elaborate fixtures to stabilise the head, neck, and torso (Almosnino et al., 2010; Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Prushansky et al., 2005). Previously reported methods have also emphasised the importance of being restrained at the shoulder, torso, and hip (Almosnino et al., 2010; Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Prushansky et al., 2005) however, research has acknowledged that trunk stabilisation limits construct validity and the relevance of strength measures (Olivier & du Toit, 2008) whilst also impacting the ability to process large numbers of athletes due to time available and accessibility to equipment in order to complete the measurements.

Irrespective of the equipment used to measure isometric neck strength, the populations which have been examined to date is mainly limited to symptomatic clinical populations or normative asymptomatic populations (Almosnino et al., 2010; Bohannon, 1993; Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Krause et al., 2019; Prushansky et al., 2005; Versteegh et al., 2015). The participants used in existing research were not athletic populations, therefore findings cannot be generalised and applied to trained athletes. Furthermore, findings have previously reported that the strength of the person administering the testing procedure using HHD or MMT to be a limitation, as tester strength has a major impact on the reliability of data collected (Bohannon, 1993; Krause et al., 2019). For an HHD or MMT to be used as a monitoring or screening tool, it would require the same strong person to administer and provide resistance for all tests to ensure that the resistance provided would be the same and therefore ensure the test is reliable (Bohannon, 1993). In clinical settings, where participants are weaker this would not pose a problem. However, it would be extremely difficult for one person to provide consistent and adequate force for a whole squad of athletes on a regular basis. Finally, the present study also aims to rectify ethical and safety issues associated with testing protocols which apply external pressure to the cervical spine (Conley et al., 1997) by ensuring that there is no external resistance being applied to the head and neck, and only using self-generated force, therefore decreasing the likelihood of injury.

To summarise, despite research identifying that neck strength could play a role in mitigating concussion (Collins et al., 2014; Dempsey et al., 2015; Eckner et al., 2014), the need for a reliable method of neck strength assessment which could be suitable for application in an applied sport environment has been largely overlooked. It is therefore of great interest for researchers to identify a reliable method to measure neck strength suitable for implementation in a sport environment and in a trained population.

In the future, it is anticipated that data collected via this method will inform a reliable, easily accessible alternative to laboratory-based measurements suitable for asymptomatic athletes. In-turn, due to the wider accessibility, it is thought strength and conditioning practitioners will be able to collect reliable data which could be used to guide practice surrounding neck strength training and monitoring.

Therefore, the aim of this research is to examine the reliability of a standardised method of measuring cervical neck strength in flexion, right-side flexion, extension, and left-side flexion using a PD and custom-built rack; suitable to for implementation in an applied sport environment and to be used by trained athletic populations.

2. Methods

Fourteen participants had their isometric neck strength measured in four directions: flexion, right-side flexion, extension, and left-side flexion, in the sagittal and transverse planes. This was performed in two sessions with 24 h in between each session. Measurements taken from the PD were PF measured in kg, and TPF measured in s. The dynamometer recorded force in N, the dynamometers setting allowed these values to be converted to kg upon recording. Expression of force in kg rather than N was preferred as it provided more context to the measurements. Therefore, from here onwards force will be expressed as kg, and not N. In the week prior to the data collection sessions, participants attended a familiarisation session where the PD was fitted to their height and low intensity practice trials in all four directions took place. The same investigator performed all measurements using the same method.

2.1. Participants

Participants recruited were athletes who trained with the strength and conditioning department. All participants had experience of structured strength training for > 2 years and performed strength training 3 times per week. All participants had undergone basic isometric neck strength training as part of their individualised training programs. The inclusion criteria detailed those participants should not be suffering or undergoing treatment for any head or spinal injury and could not have any known congenital spine abnormality. Prior to taking part in the study, participants attended a briefing and provided written informed consent. All procedures conformed to the declaration of Helsinki and institutional ethical approval was granted prior to any experimental procedures.

2.2. Procedure

Isometric neck strength was measured using a PD (Lafayette Dynamometer, Model 01165, Lafayette, California, USA) and a custom-built steel bracket, which was mounted to a wall in the University Strength and Conditioning Suite (Figure 1).

Figure 1: Isometric neck strength testing equipment

Participant's torso length was measured whilst seated with the head in the Frankfurt Plane. The measurement was taken from the iliac crest to the C7 vertebra using a tape measure. Once torso length had been measured, the PD was fitted to each participant.

Ensuring the head was in the Frankfurt plane, for flexion, the pressure pad was in line with the nose, superior to the eyebrows and in the centre of the forehead. In right and left-side flexion positions, the pressure pad was in line with and above the ear, avoiding the temple. In the extension position, the pressure pad was positioned in the centre of the back of the participants head (Figure 2).

Figure 2: Pushing positions: flexion, right-side flexion, extension, and left-side flexion.

To adjust the height of the PD, four metal bolts were unscrewed, and the PD moved up or down to suit the participant. To secure, the metal bolts were re-screwed and tightened (Figure 1). During the familiarisation session, low intensity practice trials were employed to assess whether the height was appropriate for each participant. Once confirmed, the height of the PD was recorded and set for each participant. This height remained consistent for both testing sessions.

To measure isometric neck strength, participants were seated on a standardised bench with their feet flat on the floor, palms flat to their thighs (Figure 2). Participants' feet were held in position by another participant throughout the test to prevent them from moving. The bench chosen did not have a back or arm rests to prevent bracing the trunk against a chair (Versteegh et al., 2015) (Figure 2).

Prior to the experimental procedure, each participant repeated three sub-maximal isometric contractions in each direction to warm up. For the experimental procedure, participants completed three maximal effort repetitions in each of the four directions with 30 s rest between each repetition. Participants were given 60 s rest whilst they changed pushing position. For every contraction completed, participants pushed until volitional failure and participants were instructed to stop pushing when they felt they could no longer maintain a strong isometric contraction. This allowed for the optimal time for peak isometric force to be determined. Results were displayed immediately on the PD screen and PF and TPF were recorded for all participants. The two data collections sessions were scheduled 24 h apart, participants repeated the protocol which required them to complete three repetitions in each of the four directions in: flexion, right-side flexion, extension, and left-side flexion (Figure 2). The order of pushing positions was randomised using a simple randomisation approach via a Microsoft Excel formula. Previously recorded positions were used to standardise the procedure.

The maximum scores in each direction for PF and associated TPF were used for analysis. All data are presented as mean ± SD. The alpha level was set to 0.05 a priori. Data analyses were performed using the SPSS Programme (IBM SPSS Statistics Software Version 26.0, SPSS Inc, Armonk, New York, USA). Peak values for PF and TPF were used for statistical analysis.

3. Results

The statistical methods chosen are used to demonstrate the reliability of the method used to measure isometric neck strength. Hedge's g was chosen to calculate effect sizes (ES) as the sample size was below 20 participants. ES of 0.20 was small, 0.50 was medium and 0.80 large (Vogt & Johnson, 2015). Systematic error in the repeatability of the trials was evaluated using paired sample t-tests; the magnitude of bias was determined from the mean ratio from ratio of limits agreement (RLOA) analysis. To measure reproducibility of the method between trials, Pearson's correlation coefficient (r) and intra-class correlation coefficient (ICC) was used to evaluate the intra-rater reliability of the method. Furthermore, to confirm absolute reproducibility, percentage co-efficient of variation (CV%) limits of agreement (LOA) (Bland & Altman, 1986) and standard error of measurement (SEM) were calculated independently of the ICC.

The descriptive characteristics of participants are presented in Table 1. The mean PF produced in all pushing positions follows: flexion: 16.92 ± 4.73 kg, right-side flexion: 16.95 ± 5.21 kg, extension: 26.73 ± 10.77 kg, left-side flexion: 17.59 ± 4.51 kg. Results show that in flexion, on average it took 4.16 ± 1.62 s to reach PF, right-side flexion: 5.01 ± 1.22 s, extension: 4.50 ± 1.64 s, and left-side flexion: 5.42 ± 1.51 s. All participants reached PF before 7 s.

3.1. Systematic bias between trials

There was no significant difference between PF in the two trials ($p > 0.05$; Table 2), this was also found to be similar for TPF (PF: flexion: $p = 0.89$, right-side flexion: $p = 0.40$, extension: $p = 0.83$, left-side flexion: $p = 0.78$; TPF: flexion: $p = 0.64$, right-side flexion: $p = 0.39$, extension: $p = 0.84$, left-side flexion: $p = 0.97$). Table 2 shows that the mean ratios for both PF and TPF are similar for both measures, however there is greater discrepancy in the mean ratios of PF and TPF in the right-side plane of movement compared to the other planes of movement (Table 2). Individual variation in PF and TPF are presented in Figures 3 and 4.

3.2. Absolute reproducibility in outcome measurements

Random error in outcome measurements is presented in Table 3. Reproducibility analyses indicate that mean change in PF between the two session was low in flexion, left-side flexion, and extension, however there was a greater change between scores between the two sessions in right-side flexion (Table 3). For TPF measurements, the greatest percentage change in scores occurred in flexion and right-side flexion. There were minor changes in extension and left-side flexion (Table 3). TPF had smaller SEM values compared to PF values. CV% values ranged from 8.9% to 10.4% for PF, and were deemed acceptable (Bland & Altman, 1986; Vogt & Johnson, 2015). However, TPF CV% were deemed large. LOA and RLOA were deemed to be acceptable for both PF and TPF, furthermore, no proportional bias was found for PF and TPF in any direction. The ES for all directions in PF were: flexion: $g = 0.04$ right-side flexion: $g = 0.32$, extension: $g = 0.08$ and left-side flexion: $g = 0.10$, they are considered small (Bland & Altman, 1986; Vogt & Johnson, 2015). These results are also mirrored in TPF: flexion: $g = 0.18$, right-side flexion: $g = 0.36$, extension: $g = 0.08$, left-side flexion: $g = 0.02$.

Table 1: Participant descriptive characteristics (Mean ± SD)

Sex	*n*	Age (y)	Seated stature (m)	Stature (m)	Body mass (kg)
Male	9	22 ± 3	0.96 ± 0.48	1.83 ± 0.49	94.1 ± 15.3
Female	5	21 ± 1	0.92 ± 0.47	1.76 ± 0.10	66.0 ± 10.6

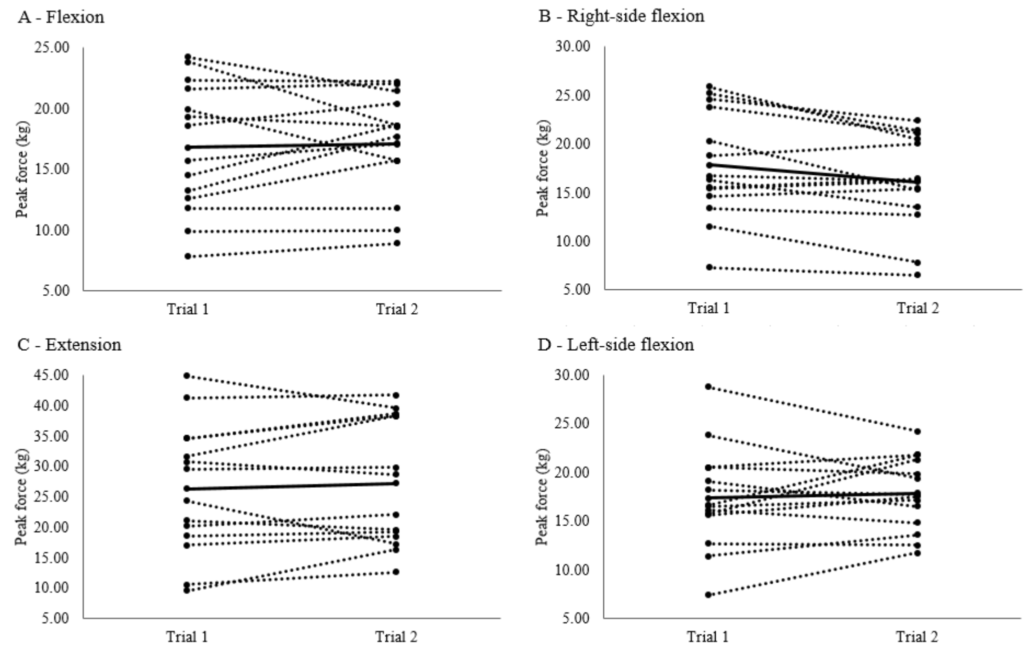

Figure 3: Individual variations in PF (A) flexion, (B) right-side flexion, (C) extension and (D) left-side flexion. Dashed lines represented individual participants and the solid line represents the group mean.

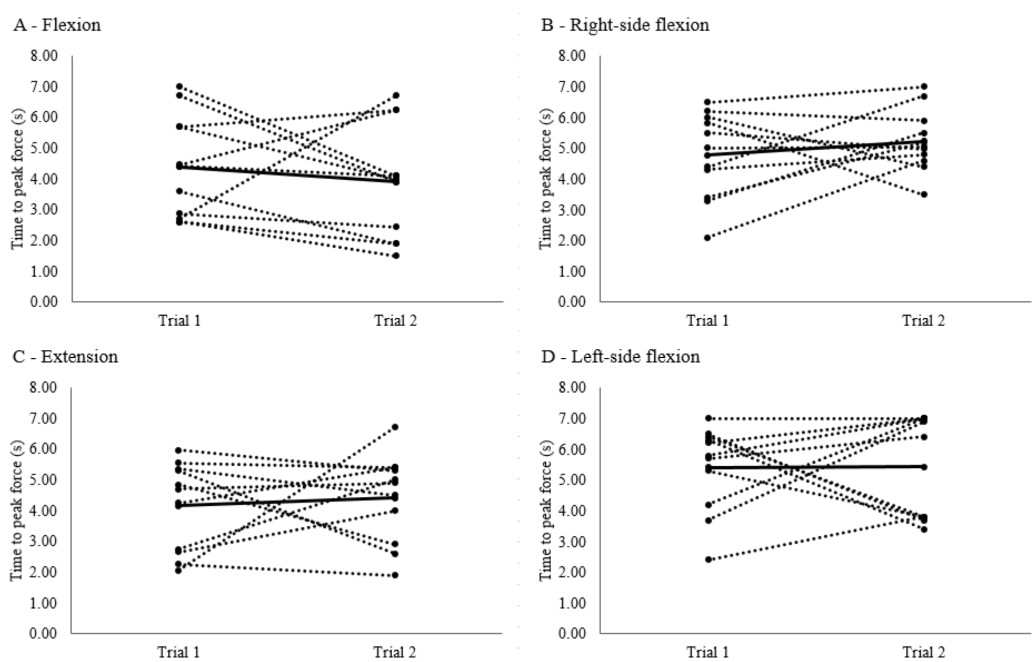

Figure 4: Individual variations in TPF (A) flexion, (B) right-side flexion, (C) extension and (D) left-side flexion. Dashed lines represented individual participants and the solid line represents the group mean.

Table 2: Systematic bias between PF (kg) and TPF (s) measurements in all four pushing positions (*p* value was determined from test re-test data) (LOA = limits of agreement, RLOA = ratio limits of agreement).

Pushing position	Variable	Mean ± SD Trial 1	Mean ± SD Trial 2	T-Test (*p* value)	LOA mean ratio	RLOA mean ratio
Flexion	PF	16.80 ± 5.31	17.04 ± 4.26	0.89	0.99	0.98
	TPF	4.31 ± 1.56	4.01 ± 1.72	0.64	1.08	1.05
Right-side flexion	PF	17.81 ± 5.57	16.10 ± 4.87	0.40	1.11	1.04
	TPF	4.78 ± 1.41	5.24 ± 1.01	0.39	0.91	0.93
Extension	PF	26.29 ± 10.77	27.16 ± 10.39	0.83	0.97	0.99
	TPF	4.56 ± 1.36	4.43 ± 1.94	0.84	1.03	0.94
Left-side flexion	PF	17.35 ± 5.27	17.84 ± 3.78	0.78	0.97	0.98
	TPF	5.41 ± 1.41	5.44 ± 1.67	0.97	0.99	1.00

Table 3: Absolute reproducibility statistics between trials 1 and 2 for determining PF (kg) and TPF (s) in all four pushing positions.

Pushing position	Variable	Δ% Mean	CV (%)	S_x	LOA (mean bias± 2s)	RLOA (mean bias x/ ÷ 2s)	SRD
Flexion	PF	1.45	8.86	0.89	5.83 to -5.35	1.48 to 0.94	2.48
	TPF	-7.05	25.69	0.32	4.04 to -3.44	0.67 to -0.47	0.88
Right-side flexion	PF	-9.59	9.57	0.98	6.14 to -2.72	0.17 to -0.07	2.73
	TPF	9.67	23.90	0.26	3.64 to -2.72	0.38 to -0.28	0.72
Extension	PF	3.30	10.00	1.96	8.69 to -6.95	0.18 to 0.14	5.44
	TPF	-2.87	28.54	0.32	3.83 to -3.57	0.52 to -0.42	0.89
Left-side flexion	PF	2.80	10.43	0.85	6.78 to -5.80	0.22 to -0.14	2.73
	TPF	0.50	25.45	0.32	4.32 to -4.26	0.41 to -0.37	0.89

Δ = Change, CV% = Coefficient of variation percentage, S_x = Standard error of the mean, SRD = Smallest real difference

Table 4: Relative reproducibility for determining PF (kg) and time to TPF (s) in all four pushing positions.

Pushing position	Variable	ICC	ICC CI	*r*
Flexion	PF	0.85	0.60-0.95	0.86*
	TPF	0.35	-0.22-0.75	0.34
Right-side flexion	PF	0.92	0.77-0.97	0.92*
	TPF	0.14	-0.47-0.66	0.14
Extension	PF	0.94	0.80-0.98	0.94*
	TPF	0.39	-0.18-0.77	0.40
Left-side flexion	PF	0.78	0.49-0.94	0.81*
	TPF	0.00	-0.58-0.58	<0.01

ICC = Intraclass correlation coefficient, ICC CI = Intraclass correlation coefficient confidence interval, *r* = Pearson's correlation coefficient. *Significant to 0.05 level.

3.3. Relative reproducibility in outcome measurements

Reproducibility statistics for the method used to test PF and TPF are presented in Table 4. This method has strong relative reproducibility for PF in all directions. However, Table 4 indicates weak relative reproducibility of TPF as ICC and *r* values were found to be below the accepted levels for good to excellent reliability.

4. Discussion

Despite there being clinical studies, which measure neck strength using laboratory equipment (Almosnino et al., 2010; Bohannon, 1993; Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Krause et al., 2019; Prushansky et al., 2005; Versteegh et al., 2015) a reliable and accessible method to measure isometric neck strength in a sport environment, has yet to be established. The primary aim of this paper was to examine the reliability of a method of measuring isometric neck strength using a PD and custom-built rack, suitable for practical use in an applied environment. The reliability statistics employed in this study allows for greater comparison to clinical methods used to measure isometric neck strength and establishes whether this method can yield reliable results.

Data presented supports the use of a PD fixed onto a wall mounted bracket in an applied sport and exercise environment, as it demonstrates similar levels of reliability to methods used in clinical research and laboratory-based studies of isometric neck strength. For example: ICC scores for flexion, right-side flexion, extension, and left-side flexion for a range of different clinical, laboratory and custom-built equipment, have been reported between 0.80 – 0.99 (Almosnino et al., 2010; Chiu & Lo, 2002; Dvir & Prushansky, 2008; Jordan et al., 1999; Prushansky et al., 2005). ICC scores for the method and equipment used in this research range between 0.78 and 0.94 across all four directions, with CV% values ranging from 8.9% to 10.4% for PF. Left-side flexion demonstrated the lowest reliability of the four directions, a possible explanation of this is the dominance or sidedness of the athletes. Unfortunately, this data was not collected, however further investigation is warranted to understand how this may impact the reliability of the left-side flexion measure. Overall, despite the range in the comparative ICC and CV% scores, which is likely to be attributed to the difference in equipment, experimental conditions and participants, the results indicate isometric neck strength can be measured reliably within a sport environment without visiting a laboratory or using elaborate, specialist equipment; therefore, enabling greater accessibility for athletes who are at risk of sustaining a TBI, or undertaking rehabilitation post injury.

Despite limited analysis of the reproducibility of TPF measurements of the cervical spine musculature in athletes, there were notable differences in levels of reliability found in previous research in clinical settings. It has been reported that CV% for rate of force development (RFD) measured using custom-built laboratory equipment, ranged from 5% - 9% with ICC scores ranging between 0.90 - 0.99 in active adult males (Almosnino et al., 2010). Our results showed CV% ranged from 23% – 29%, with ICC scores ranging between 0.00 - 0.39 in athletes. The findings of this present study do corroborate results from existing research investigating the reliability of methods used to measure RFD in sport environments. For example, RFD has been found to be less reliable than maximal force-based qualities when assessed via force plates in a range of different movements such as: countermovement jumps (CMJ), drop jumps (DJ) and isometric mid-thigh pull (IMTP) (Dos'Santos et al., 2018; Hernández-Davó & Sabido, 2014; Hori et al., 2009).

It is not clear if the incomplete stabilization of the torso was associated with the poor reliability of the TPF measure. The removal of torso stabilization may have led participants to accelerate their head into the pad thus creating differences between readings. However, if this were so, it could have been expected that the PF measurements would also have been unreliable, however PF was found to be a highly reliable measure of isometric neck strength.

An unexpected finding identified that on both data collection sessions, all participants reached their PF within 7 s of beginning the isometric contraction, in all directions. Compared to TPF for other muscles this is significantly longer, however as there is little information available investigating TPF of the neck musculature, there were no prior expectations of what this figure may have been.

Overall, the preliminary findings presented here support the use of this equipment to measure PF in an applied sport and exercise environment as it demonstrates a reliable, less time consuming and complex method of measuring isometric neck strength. This method allows for ongoing monitoring and evaluation of neck strength for athletes during a season, which could see those who are at risk of sustaining TBI to be identified prior to sustaining an injury, rather than only accessing one-off measurements at the point of injury. This could allow for tailored recommendations to be prescribed to athletes in order to minimise the incidence of concussion or assist in the return to play from concussion. Furthermore, the test utilises easily movable equipment, which allows for the equipment to be mounted in an area which athletes use every day, such as a gym or training facilities. This will increase athletes' access to the equipment and in turn also increase the amount of reliable data available for practitioners to analyse and use to inform training prescription. This could lead to an improved understanding of the role neck strength plays in sport and concussion.

To conclude, the aim of this study was to determine whether the measuring of isometric neck strength using a PD mounted on a custom-built bracket exhibited suitable levels of reliability appropriate for use in a sport environment. Findings from this study are important as current methods of measuring isometric neck strength are largely clinical assessments, laboratory based, and require complex equipment which results in them being inaccessible for athletes who could benefit from monitoring and evaluation of their neck strength.

The method detailed here is a reliable method of quantifying PF of the neck musculature in asymptomatic athletes, in a sport environment. However, this method is not reliable when measuring TPF. The results of this research may prove valuable in the assessment and monitoring of isometric neck strength for athletes who take part in sport. Implementation of this equipment and method in future research should aim to identify the effects that sports have on peak isometric neck strength. Furthermore, future research should seek to measure isometric neck strength in contact sports and analyse the impact that tailored recommendations as a result of monitoring peak isometric neck strength, has on the incidences and return to play from concussion in contact sports.

Conflict of Interest

The authors declare no conflict of interests.

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