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Highlights in elite sports and performance enhancement: 2021/22

Edited by
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Highlights in elite sports and performance enhancement: 2021/22

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Editorial: Highlights in elite sports and performance enhancement 2021/22

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exercise, physical training, olympics, team-sports, recovery

Editorial on the Research Topic
Highlights in elite sports and performance enhancement 2021/22

1. Introduction

Elite sports and performance enhancement are deeply associated. Sports scientists and coaches are always observing, evaluating, planning, and acting to improve their results. In this sense, the evidence-based practice approach is relevant. Therefore, the current research topic (RT) – Highlights in Elite Sports and Performance Enhancement 2021/22 has the aim to deliver a selection of high-impact articles written by leaders in the field. A diversity of research across the Elite Sports and Performance Enhancement section is spotlighted.

2. Articles

The current RT has nine articles in total. Five original research articles (Poignard et al.; Dimundo et al.; Höög and Andersson; James et al.; Riazati et al.), one opinion article (Brocherie and Beard), one systematic review (Millet et al.), one brief research report (Kubayi and Larkin), and one perspective article (Almqvist et al.).

Poignard et al. studied the impact of recovery practices in tennis players and found that a combination of 2–3 techniques has been used. However, cooling techniques were the most widely used modality and attenuated muscle soreness, regardless of the training type (Poignard et al.).

James et al. reported the volume and intensity of locomotor activities in international men's field hockey matches over a 2-year period. The first playing quarter had the highest physical demands, but match physical demands varied by playing position. Also, there was a strong negative relationship between total playing time and the intensity of locomotor activities. These data may help to inform training, recovery, and planned substitutions practices (James et al.).

Höög and Andersson described the physical capacity of elite TeamGym athletes and analyzed difference between sex and experience level (i.e., junior vs. senior athletes). Their results showed males performed better than females and seniors performed better than junior TeamGym athletes (Höög and Andersson).

Through a multidisciplinary research approach, Dimundo et al. investigated the attributes involving selection in under-15 rugby union players at an English Premiership Regional Academy. The authors concluded that anthropometric and physiological qualities (e.g., body mass, strength, and speed) are better explained selection than cognitive aspects and birth quartiles (Dimundo et al.).

Riazati et al. investigated the time course of recovery for gait and neuromuscular function immediately after and 24-h post-interval training. They found that following a high intensity interval training session, master runners experienced significant impairments to both central and peripheral drive, besides changes in gait kinematics and force. Although most of the runners recovered within 24-h, a small number did not. These authors concluded that waiting for a full recovery after running may help to prevent overuse injuries (Riazati et al.).

To bridge the gap between research and practice in sports, Brocherie and Beard suggested a global approach. Among other things, they suggested improving collaboration with coaches/managers and athletes, establishing trust and building relationships with academics or other sports industry infrastructures, and improving quality decisions in practice (Brocherie and Beard).

Millet et al. performed an extensive and complex bibliometric analysis of research involving all summer and winter Olympic Sports. Interestingly, nine (i.e., 18%) out of 50 Olympic sports represented 17,252 articles out of 25,003 articles in total, corresponding to 69% of all selected publications (Millet et al.).

Kubayi and Larkin studied the 2019 Africa Cup of Nations Soccer Championship focusing on the match statistics associated with success. Their findings showed that the winning teams presented a greater number of total shots, shots on target, and shots from counter-attacks compared to the losing squads (Kubayi and Larkin).

Almqvist et al. presented a scientific perspective on reducing ski-snow friction to improve performance in Olympic cross-country skiing. The authors highlight that performance on "narrow skis" has improved extensively in recent decades and that future insights into how best to reduced ski-snow friction could allow for additional advancements (Almqvist et al.).

3. Final considerations

The current RT highlights the importance of evidence-based practices in improving sports performance. The articles included in this RT reveal the variety of research in the field. The studies range from investigations into recovery practices, physical capacities, attributes, the time course of recovery, and performance improvements. The findings provide new insights and contribute to a better understanding of sports performance enhancement. The importance of improving collaboration between researchers, coaches, athletes, and sports industry infrastructures was also emphasized. This RT offers useful information for sports scientists and coaches, as they strive to improve sports performance.

Author contributions

KG, GRM, and SB conceived the idea, wrote the first draft, worked on all drafts, and formatted the manuscript for submission. All authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The Impact of Recovery Practices Adopted by Professional Tennis Players on Fatigue Markers According to Training Type Clusters

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Introduction: Modern tennis players face congested schedules that force the adoption of various recovery strategies. Thus, recovery must be fine-tuned with an accurate quantification of its impacts, especially with regards to training-induced fatigue. The present study aimed to examine the training type clusters and recovery practices adopted by elite tennis players under ecological training conditions. The respective impacts of training type clusters and recovery techniques on subjective variables, which reflect the players' recovery perceptions, were subsequently determined.

Methods: During 15 consecutive months, a total of 35 elite tennis players filled out questionnaires to report their daily training load, training session content, adopted recovery modalities after training, and perceived recovery.

Results: The hierarchical analysis identified three clusters: "combined tennis and S&C training," "predominant tennis training" and "predominant S&C training." *Muscle soreness* and *perceived fatigue* were not significantly different among these three clusters ($p = 0.07$–0.65). Across the 146 recorded training and recovery sessions, players primarily employed a combination of 2 or 3 modalities, with cooling strategies being the most widely used technique (87.6%). Mixed linear models revealed that independent of training clusters, cooling strategies significantly reduced muscle soreness (Δ*muscle soreness*: $\beta = -1.00$, $p = 0.02$). Among the cooling techniques used, whole-body cryotherapy induced a greater perceived recovery than cold-water immersion ($p = 0.02$).

Conclusion: These results showed that perceived recovery was not sensitive to training clusters or the associated acute training load. However, cooling strategies were relevant for the alleviation of tennis training-induced soreness. This study represents an initial step toward a periodized approach of recovery interventions, based on the interactions between training load, training contents, and perceived recovery.

Keywords: training load, recovery practices, cryotherapy, cooling strategies, muscle soreness, perceived fatigue

INTRODUCTION

Elite tennis players face a continuous increase in competition density, resulting in increased physical demands and injury rates (Fu et al., 2018). To be well-prepared, players begin their training seasons around the middle of November, with a preparatory phase lasting between 5 and 7 weeks. Then, players alternate between pre-competitive and competitive phases with a training vs. competition ratio around 40–60% (Kovacs, 2018). However, these training phases are crucial, not only for fitness training but also for the development of technical and tactical skills. Composite training, combined with a congested schedule, can result in several states of fatigue, requiring coaches and athletes to implement appropriate recovery periods and techniques. Therefore, understanding (i) the nature of fatigue induced by this style of training and (ii) the recovery status of elite tennis players is necessary to optimize the periodization of appropriate recovery techniques (Kellmann et al., 2018).

Tennis-induced fatigue is the consequence of numerous factors, such as playing style, gender, training status, age, playing surface, ball type, and environment (Fernandez-Fernandez et al., 2009), which result in various physiological and psychological disturbances. These potential stressors can be evaluated through training/competition load indicators designed to assess whether an athlete is adapting well to the training, competition loads, and stimuli. The Session-Rating of Perceived Exertion (sRPE) is an ecological and non-invasive training/competition load indicator which has been validated for various sports, including tennis (Foster et al., 2001; Gomes et al., 2015; Haddad et al., 2017). Recent studies have evaluated the loads imposed during tennis competitions (Ojala and Hakkinen, 2013; Duffield et al., 2014), but few studies have addressed the daily or weekly distribution of training sessions and training loads imposed on an elite tennis player under ecological conditions (Murphy et al., 2015; Vescovi, 2017).

To monitor an athlete's recovery status and to measure how the recovery modality affects post-exercise recovery, the Hooper questionnaire (Hooper and Mackinnon, 1995), which is based on multiple subjective variables, has been widely used in several studies (Bleakley et al., 2012; Bieuzen et al., 2013; Duffield et al., 2014; Costello et al., 2015; Schaal et al., 2015). Subjective variables have also recently been shown to be sensitive to changes in training loads during applied professional team sports research (Moalla et al., 2016; Thorpe et al., 2017). However, to our knowledge, no study has assessed the impacts of training loads on subjective recovery in high-level tennis players.

Investigating the effects of professional training load and recovery modalities are paramount, given that a wide variety of recovery techniques (e.g., water immersions, active recovery, stretching, whole-body cryotherapy, compression garments…) are available to tennis players. However, inconsistent results have been reported regarding the impacts of different recovery techniques on the fatigue induced by training or competition (Bahnert et al., 2013; Halson et al., 2014; Roberts et al., 2015; Dupuy et al., 2018; Tavares et al., 2019). Elite tennis centers have developed some practical guides regarding recovery techniques that are provided to coaches and athletes; however, no systematic evidence has been reported regarding the efficiencies of these techniques. Recently, a study reported that 80% of competitive tennis players adopted multiple post-exercise recovery strategies, primarily foam rolling, cold-water immersion, hot-water immersion, and the intake of protein shakes (Fleming et al., 2018). However, research examining the effects of these techniques on tennis players remains limited. For example, only one study found that combining cold water immersion with compression garments was able to alleviate post-training muscle soreness (Duffield et al., 2014). Some recent studies have improved the understanding of recovery for specific disciplines, including professional football and rugby, and have promoted recommendations for specific recovery strategies that should be applied to the highest-level athletes, based on the specific demands of these sports (Nédélec et al., 2015; Tavares et al., 2017). Thus, a better understanding of the efficiencies of the post-exercise recovery routines adopted by tennis players could help fill the gap between scientific evidence and actual practice.

In this context, the aims of the study were as follows: (i) to constitute groups according to training contents and training loads and to analyze its effects on subjective variables, used to represent perceived recovery; and (ii) to provide an overview of the recovery habits adopted by elite tennis players and to determine their effects on subjective variables, according to the defined training groups. To address these two aims, we used a hierarchical clustering approach to gather the entire dataset of training sessions into subgroups according to training content, duration, and load. This approach allowed the inclusion of the uniform and consistent categorical variable of "training" into a linear mixed model, to evaluate the impacts of recovery modalities on subjective recovery variables. We hypothesized that different clusters would elicit significantly different effects on perceived fatigue and muscle soreness (Moalla et al., 2016). Based on previous literature, we consequently expected that cold recovery interventions would have larger impacts on muscle soreness than other interventions.

METHODS

Participants

Sixteen male players from the Association of Tennis Players (age $= 19.0 \pm 3.0$ years; stature: 185.5 ± 7.8 cm; body mass: 77.8 ± 10.1 kg; years on circuit $= 4.5 \pm 5.0$), sixteen female players from the Women's Tennis Association (age $= 20.1 \pm 4.3$ years; stature: 171.6 ± 5.5 cm; body mass: 60.5 ± 4.0 kg; years on circuit $= 3.7 \pm 4.0$), and three female junior players from the International Tennis Federation engaged in Junior Grand Slam (age $= 16.0 \pm 0.7$ years; stature: 171.0 ± 5.0 cm; body mass: 60.0 ± 5.0 kg), were included in this study. No male junior players were included in this study. At the time of the experiment, the male players were ranked (median over the 15 months of the experiment) as follows: 16 players were in the top 1,000, including 12 in the top 500. Female players were ranked as follows: 16 players were in the top 1,000, including 9 in the top 500, and 3 with no professional ranking. Players and their parents (for minors) were informed of the procedures before they provide their written informed consent. All procedures conformed to the standards of the Declaration of Helsinki, and the study was approved by the ethics committee.

Procedure

The training load, subjective variables, and recovery techniques were monitored, using an application designed specifically for this study. For each training day, players filled out a training load questionnaire, a recovery modalities form, and a psychometric questionnaire. Players reported the contents, duration, and intensity of both morning and afternoon training sessions. At the end of the day, before recovery (PRE) and strategies being implemented, participants indicated all of the recovery modalities that they were planning to use (from 1 to 5 recovery interventions) and filled out the psychometric questionnaire. The next morning (12–16 h after recovery, POST), before training, players filled out the same psychometric questionnaire to isolate the potential effects of the recovery modality on the subjective variables (**Figure 2**). All sessions performed by the participants were recorded over 15 consecutive months, only in the presence of the same investigator at the training center (201 days over the 15 months). No training sessions were recorded during the competitive phase. Prior to the study, all players were familiarized with all questionnaires included in the application.

Training Monitoring

The training content was considered to reflect "tennis training" when players trained on a tennis court. These training sessions included technical and tactical drills, services, point play, and non-official match play, which developed technical and tactical skills. These workouts elicited specific motor tasks associated with tennis practice, including lateral sprints, rushes, cutting-maneuvers, smashes, drop landing, and jumps. "Strength and conditioning training" (S&C) corresponded to all off-court training session, for which the primary objective was developing physical fitness specific to tennis, including aerobic exercise (high-volume, low-intensity work), anaerobic exercise (interval training, using tennis-specific work/rest intervals), speed and power training (sprinting and explosive exercises), strength training (high-repetition, low-resistance exercise), and plyometric training. Within 30 min following morning and afternoon training sessions, players indicated their rate of perceived exertion (RPE) on a ten-point category-ratio scale (CR-10 Borg Scale) modified by Foster et al. (2001). We then assessed sRPE training load for the morning and afternoon training sessions, using the methods described by Foster et al. (2001). Total sRPE training load was calculated as the sum of morning and afternoon sRPE training load values.

Psychometric Questionnaire

The psychometric questionnaire was adapted from the Hooper questionnaire (Hooper and Mackinnon, 1995). Immediately after training, and just before recovery, players were asked to score the 3 following subjective variables: *muscle soreness, stress,* and *perceived fatigue*. The next morning, before training, players scored the same 3 variables and 2 additional factors: *sleep quality* and *perceived recovery*. All 5 variables were presented and rated on a 0–10 cm visual analog scale (VAS), with 0.1-cm accuracy. Changes between PRE and POST measurements for *muscle soreness*, *perceived fatigue,* and *stress* were calculated. To minimize bias, only one investigator collected all data, to preserve consistency and homogeneity. Before the study, all players were first educated regarding the meanings of the self-reported items, according to the definitions described by the Hooper questionnaire (Hooper et al., 1995). Each tennis player was blinded to the results of the other participants. Qualitative indicators used to assist players with reporting perceptions in the psychometric questionnaire were as follows:

- *Muscle soreness: 0 = no muscle soreness to 10 = Very high muscle soreness*
- *Perceived fatigue: 0 = no perceived fatigue to 10 = extremely exhausted*
- *Stress: 0 = no stress to 10 = extremely stressed*
- *Sleep quality: 0 = excellent to 10 = very bad, with insomnia*
- *Perceived recovery: 0 = No at all to 10 = Completely recovered.*

Recovery Modalities

A total of 15 different recovery modalities were implemented by players and were pooled into 5 distinct categories. The recovery modalities that aim to decrease muscle temperature were considered to be "Cooling strategies," including whole-body cryotherapy (WBC) (3 min at −110°C), cold-water immersion (CWI) (11 min at 11°C), and contrast water therapy (CWT) (7 repetitions of 1 min/1 min at 11/40°C). Hot-water immersion and steam room modalities were classified as "heating strategies." We pooled foam-rolling and stretching into a "Flexibility techniques" category, as these techniques are known to improve the range of motion during passive conditions (Sands et al., 2013; Macdonald et al., 2014). Active recovery, electrostimulation, thermoneutral water immersion, compression garments (Agu et al., 1999; Menetrier et al., 2015), and external pneumatic compression were categorized as "lower limb blood flow stimulation." We classified all therapeutic procedures that required the use of physical agents (physiotherapists and osteopaths) into the group "Physiotherapy techniques," including joint mobilization, massages, and osteopathy.

Data Collection and Selection

A total of 146 sessions corresponding to the predominant training situations performed by tennis players, were selected and analyzed over the 387 sessions recorded (**Figures 1**, **2**) in order to preserve the homogeneity of the data. These training situations corresponded to two or three training sessions per day and included at least one S&C training session and one tennis training session. Sessions that included no training, two similar training sessions (e.g., two tennis training) or four training sessions in a day were excluded from our analysis (**Figure 1**). Sessions that included a recovery technique which did not follow general guidelines were also excluded from further analysis. A total of 91% of the monitored sessions were recorded during a preparatory phase and 9% of the monitored sessions during a pre-competitive phase. Players filled an average of 4.1 ± 3.5 questionnaires over the 146 sessions.

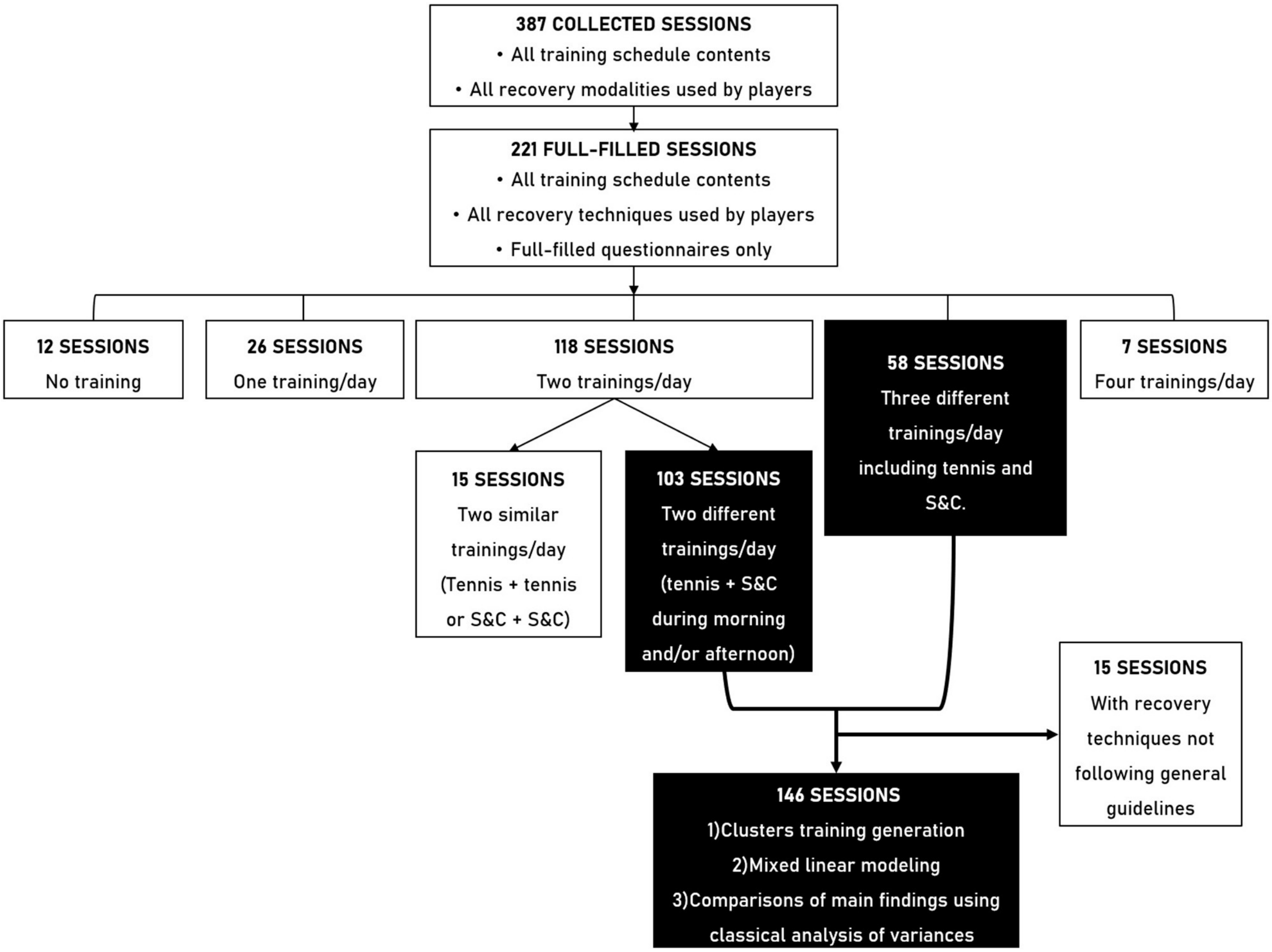

FIGURE 1 | Selection of sessions flow chart. White boxes represent excluded sessions and the corresponding exclusion criteria while black boxes represent selected sessions and the corresponding inclusion criteria.

Statistical Analysis

All variables are presented as the mean ± standard deviations (SD). To divide the 146 training sessions into training profile clusters, we used principal component analysis, followed by the application of hierarchical clustering for the principal components, using *FactoMineR* (version 1.41) in R Studio (Version 1.1.463). The selection variables were total sRPE training load, total tennis training session duration, and total strength & conditioning training session duration. The squared Euclidean distances technique was used, and we fixed the possible number of clusters between 2 and 5. To investigate how training profile clusters and recovery modalities affected subjective variables, we employed linear mixed-effects models, which are an extension of linear regressions, to consider the repeated measurements within participants (146 recorded sessions from 35 players). We used the *lmer* function of the lme4 (version 1.1-21) package in R Studio, where output subjective variables (Δ*muscle soreness*, Δ*perceived fatigue*, *sleep quality*, and *perceived recovery*) were analyzed into separate models. We included a per player random intercept and a fixed effect for the input variables (clusters and recovery modalities). Interactions between the clusters and recovery modalities were tested, but interactions were not examined between recovery modalities, due to an insufficient number of observations. *P*-values were obtained using Welch-Satterthwaite *t*-tests, for all full models, and the significance level was fixed at $p < 0.05$. If an association between an input variable and an output subjective variable was observed, we performed an additional test [Likelihood Ratio Test (LRT)], using an analysis of variance (ANOVA) to compare a model without the input variable against a model with the input variable. All assumptions (linearity, absence of collinearity, independence, and normality of residuals) were checked with the *plot, qqnorm* function of the car package (3.0–2) in R. When a significant effect was observed in the linear mixed-effects models, differences between modalities within the same recovery category were assessed, using a One-Way ANOVA for normally distributed data or a Kruskal-Wallis test for non-normally distributed data. Similar statistical analyses were performed to determine differences between clusters for the subjective variables. When a significant main effect or interaction was observed, a Bonferroni

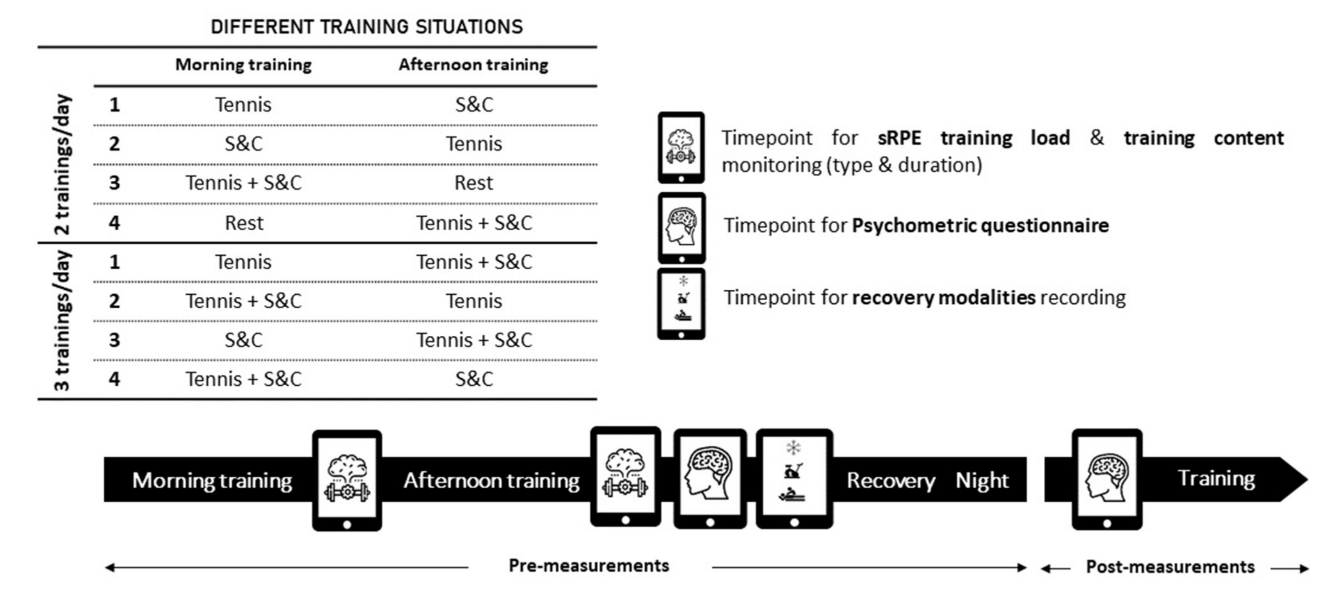

FIGURE 2 | Overview of the experimental design. Tennis, tennis training; S&C, strength and conditioning training; Rest, no training. Pre-measurement, at the end of the training day; Post-measurement: the next morning, after recovery and before training.

post-hoc test was used to locate the difference. The level of significance was set to $p < 0.05$. These latter statistical analyses were conducted using the IBM Statistical Package for the Social Sciences (SPSS) (IBM SPSS Statistics, 20.0.0, SPSS Inc., USA). Effect sizes (ESs) were calculated using the following formula, for non-parametric data: $r = z/\sqrt{N}$, where refers to the z value obtained from the Mann-Whitney U test and N refers to the number of observations (Fritz et al., 2012). Interpretations were based on Cohen's formula, where: $r = 0.2$, 0.5, and 0.8 were considered to be small, medium, and large, respectively.

RESULTS

Cluster Analysis

The hierarchical cluster analysis identified three training type clusters (**Figure 3**) which were consistent with three theorical training microcycles that are recommended during training periods. The first cluster defined as "Combined tennis and S&C training," was statistically defined by a lower total duration of tennis training (−13.7 min), a lower total strength training duration (−17.2 min), and a smaller total sRPE training load (−187.7 A.U) compared with the means for all clusters (overall means). The second, defined as a "Tennis-specific oriented training" cluster, was statistically defined by a higher total tennis training duration (+86.1 min) and a lower total strength training duration (−28.8 min) compared with the overall means. The third, defined as a "S&C oriented training" cluster, was statistically defined by a higher total strength training duration (+70.3 min) and a higher total sRPE training load (+482.1 A.U) compared with the overall means. Kruskal-Wallis analyses showed no significant differences among clusters for *muscle soreness* ($p = 0.10$, ES: −0.19 to −0.09) and *perceived fatigue* ($p = 0.07$, ES: −0.16 to −0.08). We observed no significant differences among clusters for Δ*muscle soreness* ($p = 0.65$), Δ*perceived fatigue* ($p = 0.98$), *sleep quality* ($p = 0.11$), or *perceived recovery* ($p = 0.12$). The results for the stress subjective variables were not interpretable as a median, and the values of the lower and upper quartiles for Δ*stress* were 0 (−0.1 to 0.1) and 0.4 (0.0–1.6), respectively, for *stress* reported on PRE questionnaires.

Recovery Techniques Adopted by Professional Tennis Players

Most of the players (69.2%) used a combination of 2 (41.8%) or 3 (27.4%) recovery modalities, with an average of 2.6 ± 1.0 techniques per session. Cooling (CWI, CWT, and WBC) was used by 87.6% of the players (**Table 1**). Passive mobilization was the second-most commonly used technique (61.6%), followed by physiotherapy techniques (47.9%), lower limb blood flow stimulation (46.5%), and heating strategies (14.3%).

Mixed Linear Model Results

We did not observe any significant interactions between clusters and recovery modalities (all $p > 0.05$). The linear mixed-model regression analysis revealed that cooling strategies were associated with Δ*muscle soreness* ($\beta = -1.00$, 95% confidence interval [CI] [−1.8, −0.1], $p = 0.02$). The LRT confirmed that cooling strategies significantly reduced muscle soreness ($\chi^2 = 4.93$, $p = 0.02$).

Comparison of Cold Recovery Modalities

Because we noticed a significant association between cooling strategies and Δ*muscle soreness*, we compared the effect of each modality on the same subjective recovery variables. We observed no significant differences between CWI, CWT and WBC for Δ*muscle soreness* ($p = 0.33$), Δ*perceived fatigue* ($p = 0.60$) or *sleep*

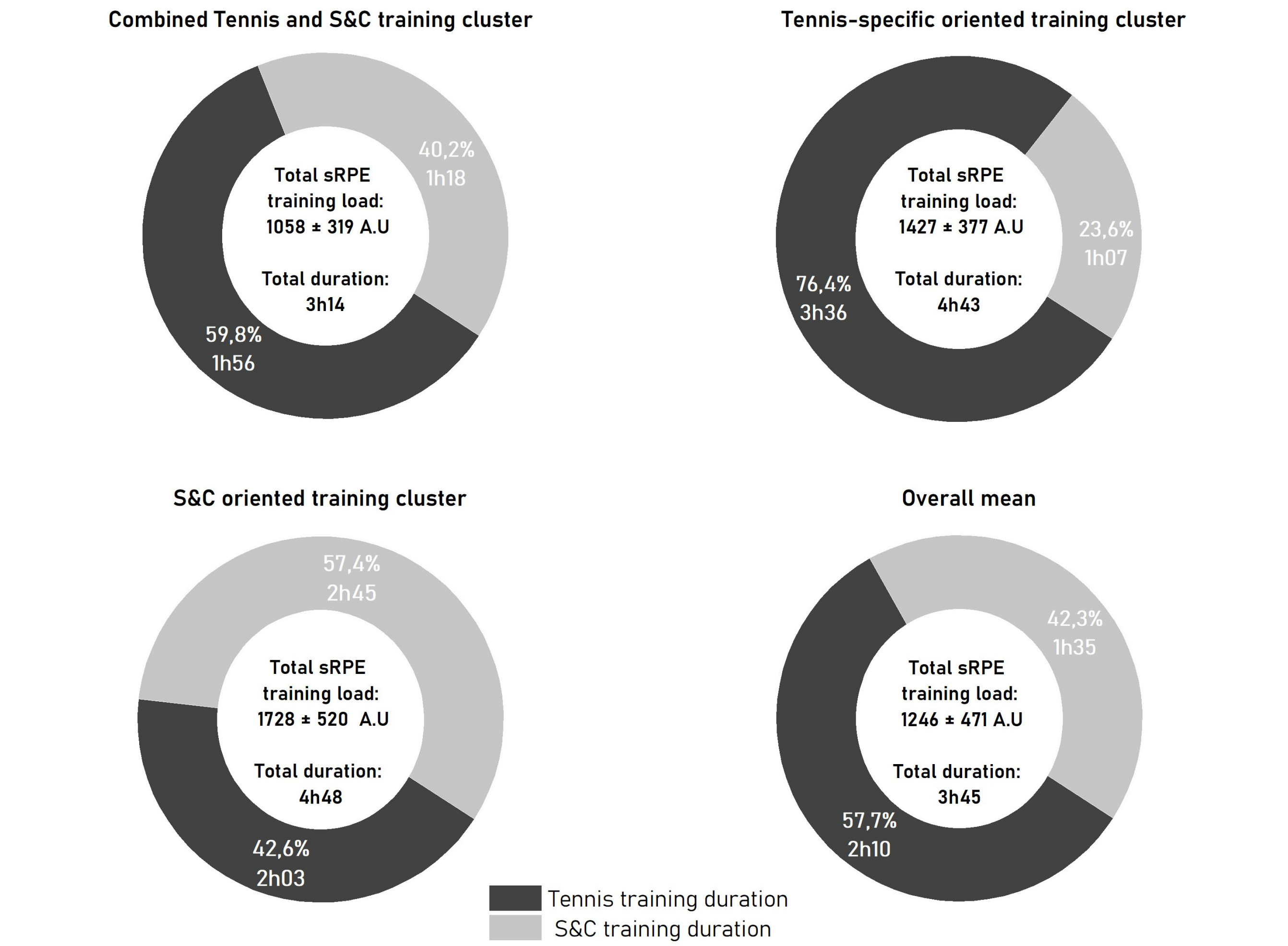

FIGURE 3 | Mean ± SD of the three selections variables for each of training clusters and the overall mean. Overall mean: average of the 146 sessions; S&C (strength and conditioning) training duration expressed in hours and %; tennis training duration expressed in hours and %; total sRPE training load (total daily training load) expressed in A.U.; total duration of training in hours.

quality ($p = 0.45$). Kruskal-Wallis analyses revealed significant differences between cold recovery modalities ($p = 0.03$) for *perceived recovery,* with a higher score for WBC compared with CWI ($p = 0.02$). No significant differences were observed among the other cooling techniques (all $p = 1.0$).

DISCUSSION

The present study reported 3 major findings: (i) professional tennis players consistently adopt recovery methods after training, primarily utilizing a combination of 2–3 techniques, with cooling techniques being the most widely used modality; (ii) *muscle soreness* and *perceived fatigue* are not significantly different depending on training profile clusters; and (iii) only cooling strategies were found to be efficient for attenuating *muscle soreness,* regardless of the training type cluster.

Given that 91% of considered sessions were monitored between mid-November and the end of December, our data may represent the distribution of training loads during the preseason period. Tennis players daily experienced a total sRPE training load of 1,246 ± 471 A.U. per day, which is similar to the total sRPE training load of 1,267 A.U. that was recently reported by Murphy et al. (2015) for high-performance junior tennis players during a 4-week pre-competition period. In more detail, the daily tennis training volume obtained in our study (130.3 ± 41.0 min) was similar to the 151.0 ± 12.1 min daily training volume reported by Murphy et al. (2015). In contrast, they observed shorter strength and conditioning volumes (45.0 ± 14.9 min), in comparison with the 95.5 ± 50.2 min observed in our study. This observation is consistent coherent with the increase in strength training loads that occur between 17 and 20 years of age, as the players involved in our study were approximately 3 years older, on average, than the players in the Murphy et al. (2015).

Three clusters, representing the different types of classic training days, were identified among the professional tennis players in this study. The "combined tennis and

TABLE 1 | Summary of recovery modalities used after a training day.

		Passive mobilization	Physiotherapy techniques	Heating strategies	Lower limb blood flow stimulation	Cooling strategies
		Number of uses per each recovery modalities				
		Foam-rolling (n = 4); Stretching (n = 86)	Joint mobilization (n = 5); Massages (n = 53); Osteopathy (n = 12)	Hot immersion (n = 20); Steam room (n = 1)	Active recovery (n = 55); Electrostimulation (n = 2); Thermo-neutral Water Immersion (n = 2); Compression garments (n = 4); External pneumatic compression (n = 5)	Whole-body cryotherapy (n = 51); Cold-Water immersion (n = 64); Contrast Water Therapy (n = 13)
		Number of recovery modalities used after a training day				
Number of recovery strategies implemented per session	Total	n				
1	17	1	2	0	1	13
2	61	27	19	5	21	49
3	40	32	26	5	23	34
4	21	22	15	6	17	24
5	7	8	8	5	6	8
Total	146	90	70	21	68	128

The total number of times players chose a specific recovery modality after a training day is reported as n.

S&C training" cluster better reflects a typical training day, as it represented the majority of monitored sessions ($n = 97$). In addition, the total sRPE training load, tennis training duration, and strength and conditioning training duration values for "combined tennis and S&C training" cluster were similar to the overall means calculated for all sessions. Thus, a typical training day appears to consist of an approximately evenly distributed volume of tennis and strength and conditioning training. Training days with a predominant volume of either tennis ("Tennis-specific oriented training" cluster, $n = 18$) or strength and conditioning ("S&C oriented training" cluster, $n = 31$) training appears to be less experienced by professional tennis players who compete in international tournaments.

Contrary to our hypothesis, the training clusters did not show any significant differences for *muscle soreness* or *perceived fatigue,* either before or after recovery intervention. This finding was not consistent with the findings of previous studies, which showed a positive correlation between training load and *muscle soreness* or *perceived fatigue* in professional football players (Moalla et al., 2016; Thorpe et al., 2017). However, this potential association remains controversial because, to our knowledge, no study has provided any theoretical and validated explanation to support these findings (Saw et al., 2016). Furthermore, *muscle soreness* and *perceived fatigue* can be elevated for up to 72 h following matches or training. Some items may have been more sensitive to differences in the clusters if additional time points had been collected later in the recovery time-course (Ojala and Hakkinen, 2013). In this context, the level of fatigue has recently been reported to be more sensitive to accumulated training days among professional football players (Thorpe et al., 2017). Future research is warranted to explore the impacts of accumulated and chronic training loads on these subjective variables in professional tennis players.

After a day of training, 86.3% of the professional tennis players included in the current study used a combination of 2–5 recovery modalities, with 69.2% of players using 2 or 3 modalities. This observation is in line with a recent study reported by Fleming et al. (2018) which indicated that 80% of competitive tennis players used multiple recovery modalities after a match. A combination of at least 2 recovery modalities appeared to be a well-integrated post-training habit among the professional tennis players involved in this study. The only study that explored the effects of a combined mixed-method recovery intervention found that the combination of 3 recovery modalities CWI, compression garments, and sleep-hygiene recommendations) was effective for reducing *muscle soreness* after twice-a-day, on-court, tennis sessions (Duffield et al., 2014). This finding could, therefore, be considered to be reflective of the progressive transfer of evidence-based knowledge into recovery practices in tennis.

More than 83% of players performed a cooling intervention (CWI, WBC, or CWT) after training, which is supported by similar recent studies, highlighting the considerable use of cooling strategies, particularlyCWI, among elite rugby players (Tavares et al., 2017), professional soccer teams (Nedelec et al., 2013), and competitive tennis players (Fleming et al., 2018). Similar to other sports, passive mobilization (stretching) and low-limb blood flow stimulation (active recovery) were also used frequently by the players included in this study (Bahnert et al.,

TABLE 2 | Results of the mixed-effects models testing the distinct effect of training clusters and recovery modalities on subjective variables.

		Δmuscle soreness			Δperceived fatigue			Sleep quality			Perceived recovery		
		β	*CI*	*p-value*	*β*	*CI*	*p-value*	*β*	*CI*	*p-value*	*β*	*CI*	*p-value*
	FIXED EFFECT												
Training clusters	Intercept	0.26	[−0.8; 1.3]	0.61	−0.60	[−1.8; 0.6]	0.32	3.85	[2.6; 5.1]	0.00	5.12	[4.1; 6.2]	0.00
	Cluster 2	−0.45	[−1.4; 0.5]	0.34	−0.52	[−1.6; 0.5]	0.33	0.44	[−0.7; 1.6]	0.42	−0.14	[−1.0; 0.7]	0.74
	Cluster 3	0.31	[-0.4; 1.0]	0.39	−0.15	[−1.0; 0.6]	0.71	0.29	[−0.5; 1.1]	0.49	−0.01	[−0.7; 0.6]	0.96
Recovery modalities categories	Cooling strategies	−1.00	[−1.8; −0.1]	0.02*	−0.48	[−1.5; 0.5]	0.33	−0.32	[−1.4; 0.7]	0.54	0.12	[−0.7; 1.0]	0.78
	Heating strategies	−0.17	[−1.0; 0.7]	0.70	−0.11	[−1.1; 0.9]	0.83	0.04	[−1.0; 1.1]	0.93	0.65	[−0.2; 1.5]	0.14
	Passive mobilization	−0.11	[−0.8; 0.5]	0.72	−0.04	[−0.8; 0.7]	0.91	−0.23	[−1.0; 0.5]	0.53	0.44	[−0.2; 1.1]	0.15
	Lower limb blood flow stimulation	−0.04	[−1.0; 0.3]	0.25	−0.26	[−1.0; 0.4]	0.48	0.06	[−0.7; 0.8]	0.87	−0.27	[−0.9; 0.3]	0.36
	Physiotherapy techniques	−0.17	[−0.8; 0.4]	0.59	0.43	[−0.3; 1.1]	0.24	0.14	[−0.6; 0.9]	0.70	0.16	[−0.4; 0.8]	0.59

*β: small point estimates; CI: 95% confidence intervals; *p < 0.05; Δ muscle soreness = muscle soreness (POST)—muscle soreness (PRE); Δ perceived fatigue = perceived fatigue (POST) perceived fatigue (PRE).*

2013). The easy access to recovery methods available at the Tennis Center may have influenced the athletes' behaviors and biased the selection of recovery routines (Bahnert et al., 2013). Because a substantial number of training sessions (146 sessions) was monitored among a large cohort of players (35 professional players), the present data can confidently be considered to be reflective of the recovery habits adopted by professional tennis players during preparatory/pre-competitive phases in a high-level environment.

Using this representative cohort, mixed linear models allowed us to independently test the impacts of clusters and recovery methods on the subjective variables. First, the absence of significant associations between subjective variables and clusters confirmed that neither *muscle soreness* nor *perceived fatigue* was related to the total sRPE training load or content. Our primary finding was that cooling techniques were significantly associated with attenuated *muscle soreness* (**Table 2**) the following day (12–16 h after training). These results are consistent with previous research that revealed positive impacts associated with CWI (Nedelec et al., 2013; Ihsan et al., 2016), WBC (Hausswirth et al., 2011), and CWT (Bieuzen et al., 2013) on decreased *muscle soreness*. Similar results were found by Duffield et al. (2014), who reported a significant decrease in *muscle soreness* the morning after a tennis training day when a combination of CWI, compression garments, and sleep education was applied. Recent research reported no positive effects for CWI or WBC on muscle soreness sustained by recreational athletes after a fatiguing protocol performed under controlled laboratory conditions, which could be imperfectly representative of the degree of muscle damage induced by professional tennis practice (Wilson et al., 2018). The common purpose of recovery techniques is to decrease cutaneous, muscle, and core temperatures (Costello et al., 2012; Bieuzen et al., 2013; Ihsan et al., 2016), to induce an analgesic effect during the first hours after exercise, via the inhibition of nociceptors. Such acute mechanisms were unlikely to influence the present measurements, as data regarding muscle soreness and other subjective variables were collected between 12 and 16 h post-recovery (Ihsan et al., 2016). Cooling more likely limited edema formation and inflammatory responses, through the modulation of blood flow (CWI, WBC, and CWT) and the stimulation of fluid transport (CWI and CWT), thereby, decreasing muscle soreness (Costello et al., 2012; Ihsan et al., 2016). We also cannot completely exclude a potential placebo effect, as demonstrated by recent studies (Broatch et al., 2014; Wilson et al., 2018), even if this observation was made in recreational athletes with very different training histories and objectives than those characteristics of professional training players.

Contrary to the results of our study, 20–30 min of massage performed after exercise has been reported to reduce delayed-onset muscle soreness for up to 72 h post-exercise (Guo et al., 2017), as confirmed by a recent meta-analysis that found that massage was the most effective technique for reducing muscle soreness (Dupuy et al., 2018). Similarly, foam rolling (Wiewelhove et al., 2019), electrostimulation (Borne et al., 2015), and compression garments (Marqués-Jiménez et al., 2015) have all been demonstrated to attenuate muscle soreness after exercise. Exercise may induce various physiological and psychological stresses, depending on numerous factors, such as mode, duration, or training status (Halson et al., 2014). However, some previous studies (Guo et al., 2017; Dupuy et al., 2018; Wiewelhove et al., 2019) have been meta-analyses, combining data from multiple various fatiguing protocols, which have very limited transfer to ecological contexts due to the lack of distinction in the levels of muscle soreness induced by exercise and the training levels of the athletes. The present study appraised real and ecological psychophysiological responses to training and recovery in professional tennis players. The potential positive effects of certain recovery interventions (foam rolling and electrostimulation), which are less commonly utilized by tennis players, may have been concealed by the use of more popular recovery techniques that have been demonstrated to be inefficient in the literature (stretching and active recovery) (Van Hooren and Peake, 2018). Although cooling strategies significantly alleviated muscle soreness, none of the cold recovery modalities that were monitored in the present study attenuated *perceived fatigue,* in contrast with the positive effects of cold modalities and/or massages that have previously been reported in the literature (Dupuy et al., 2018). Contrary to previous studies performed in elite athletes, we did not observe improved *sleep quality* following WBC and CWI (Schaal et al., 2015). However, these reports were anecdotal, and most research studies have found little evidence for improved sleep after cold application (Broatch et al., 2019).

Because the underlying mechanisms may differ between different cold techniques, we strived to distinguish the respective effects of each cooling strategy used by professional players. No significant differences between cold modalities were observed for *muscle soreness* of *perceived fatigue*. Based on previous studies, we expected a greater decrease in *muscle soreness* after CWI or CWT compared with WBC (Bleakley et al., 2012; Hohenauer et al., 2015). WBC showed a significant increase in *perceived recovery* compared with CWI. These results are in line with a study reported by Hausswirth et al. (2011) (+21.7 on a 100-point rating scale), who showed an increase in *perceived recovery* after WBC compared with passive condition 24 h after a simulated trail run. Indeed, previous studies have revealed that WBC may increase norepinephrine and dopamine release, resulting in an additional analgesic effect and the increases perception of recovery and well-being. Inversely, a previous study showed no effect of CWI on psychological recovery after exercise (Cheung et al., 2003). However, considering the time-course of subjective variable measurements (> 12 h post-recovery), these findings should be considered with caution, as the timing of norepinephrine and dopamine release in response to cooling strategies remains unclear. These latter statistical comparisons between cold modalities were different from the mixed linear model because they did not independently test the effects of each intervention. Other techniques used in combination with a cooling strategy could, therefore, influence subjective variables. The high variability in the different subjective variables confirmed that responses to recovery interventions are specific and individual.

LIMITATIONS

Some methodological considerations should be noted when interpreting the present absolute values of subjective recovery variables. First, training clusters may have elicited significantly different effects on subjective recovery variables if no recovery interventions (i.e., a control condition) had been implemented. However, this condition would not be representative of real-world professional athlete conditions. We used the linear mixed model to overcome this bias, by estimating each subjective recovery variable for each training cluster while excluding the potential effects of recovery modalities. Second, raw data of subjective variables (Δ*muscle soreness*, Δ*perceived fatigue*, sleep quality, and perceived recovery) were unfortunately not available as players mostly used a combination of modalities. Thus, linear mixed model allowed to estimate subjective variables that would likely be recorded for each recovery modalities categories (**Table 2**). Third, one should acknowledge that some key variables recognize to alter subjective recovery were not controlled in the present study, such as menstrual cycle or travel. However, the data collection period, which was restricted to the training phase, limited the potential influences of travel or jet lag on fatigue. Fourth, the data collection period was circumscribed to the training phases of players (≈ 40% of the season). On the one hand, this controlled period of time restricted the number of training sessions that could be monitored for each player. On the other hand, it limited the potential influences of travel or jet lag on fatigue.

CONCLUSION

This study showed that professional tennis players face substantial daily training loads (total sRPE training load) during training periods, with no consistent impacts on acute subjective recovery. Future research should investigate the potential impacts of accumulated training loads over longer periods of time. The benefits of recovery routines consisting of multiple recovery techniques appear to be well-anchored in practice. During general, specific preparations or during the taper period, cold modalities appear to efficiently decrease tennis training-induced muscle soreness compared with other recovery techniques. However, future research should include more data, with homogeneous repartition between recovery interventions, to compare the efficiencies of different combinations of recovery interventions. Although effective, cold recovery should be implemented at key strategic moments, to limit fatigue without blunting expected adaptations. The inter-individual variability observed among the perceived responses to training loads and recovery strengthens the necessity to perform continuous training load monitoring to improve recovery periodization, based on individual training-induced fatigue.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Committee of Sud Méditerranée IV (no 17 10 05). Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

MP, FB, BM conceived and designed research. MP conducted experiments. MP, FB, GG, QL, BM analyzed data. MP, FB, GG wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2020.00109/full#supplementary-material

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All Alone We Go Faster, Together We Go Further: The Necessary Evolution of Professional and Elite Sporting Environment to Bridge the Gap Between Research and Practice

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SETTING THE STAGE

The landscape of the professional and elite sport has changed enormously in recent years, with clubs/franchises and national federations performance support operating through specialized background staff roles. Although not uniformly embraced across all sports and countries, the expansion of such a model has led to the emergence of a managing position—generally termed performance director (Buchheit and Carolan, 2019)—to organize and supervise all the sports science and sports medicine servicing areas accessible to the head coach (and/or his technical staff) and athletes. The scientific support staffing base includes full-time sport scientists, physiologists, biomechanists, nutritionists, psychologists, and even more recently statisticians/data scientists, with some additional part-time input from expert/academic consultants (e.g., neuroscientists). Depending of the size and culture of the clubs/federations, a medical department covers the medical care and therapy related to training and competition, as well as the involvement of professional specialists for health management (Dijkstra et al., 2014). As an example, a National Football League (NFL) staff generally comprised five departments and as large as 13 full-time employees under the umbrella of the performance director (**Figure 1A**). All these departments operate in synergy and also "independently" with appropriate autonomy at times, with the performance director orchestrating the "front lines" in a holistic and comprehensive manner toward a common performance goal.

The impetus to drive a performance support model is directly related to assisting the coaching/front office staff on strategies to understand what winning looks like through analysis of key performance indicators and metrics (Halson et al., 2019). The performance model employs analysis technologies (e.g., global positioning system with embedded tri-axial accelerometers, gyroscope and magnetometer, wearable sensors) and scientific advances (e.g., innovative training or nutritional strategies) (Malone et al., 2019) to enhance player performance and maximize player availability (Drew et al., 2017) while maintaining their health integrity through an integrated health management system (Dijkstra et al., 2014). Despite the growing number of clubs/federations employing this approach, there are still many who do not choose to see this model as the vehicle to progress. Although this has been widely addressed (Bishop, 2008; Dijkstra et al., 2014; Buchheit, 2016, 2017; Coutts, 2016, 2017; McCall et al., 2016; Eisenmann, 2017; Nassis, 2017; Halperin, 2018; Sandbakk, 2018, 2019; Fullagar et al., 2019; Halson et al., 2019), here, the present opinion proposes to discuss past, actual, and new issues faced by the practitioners and researchers that are at the front

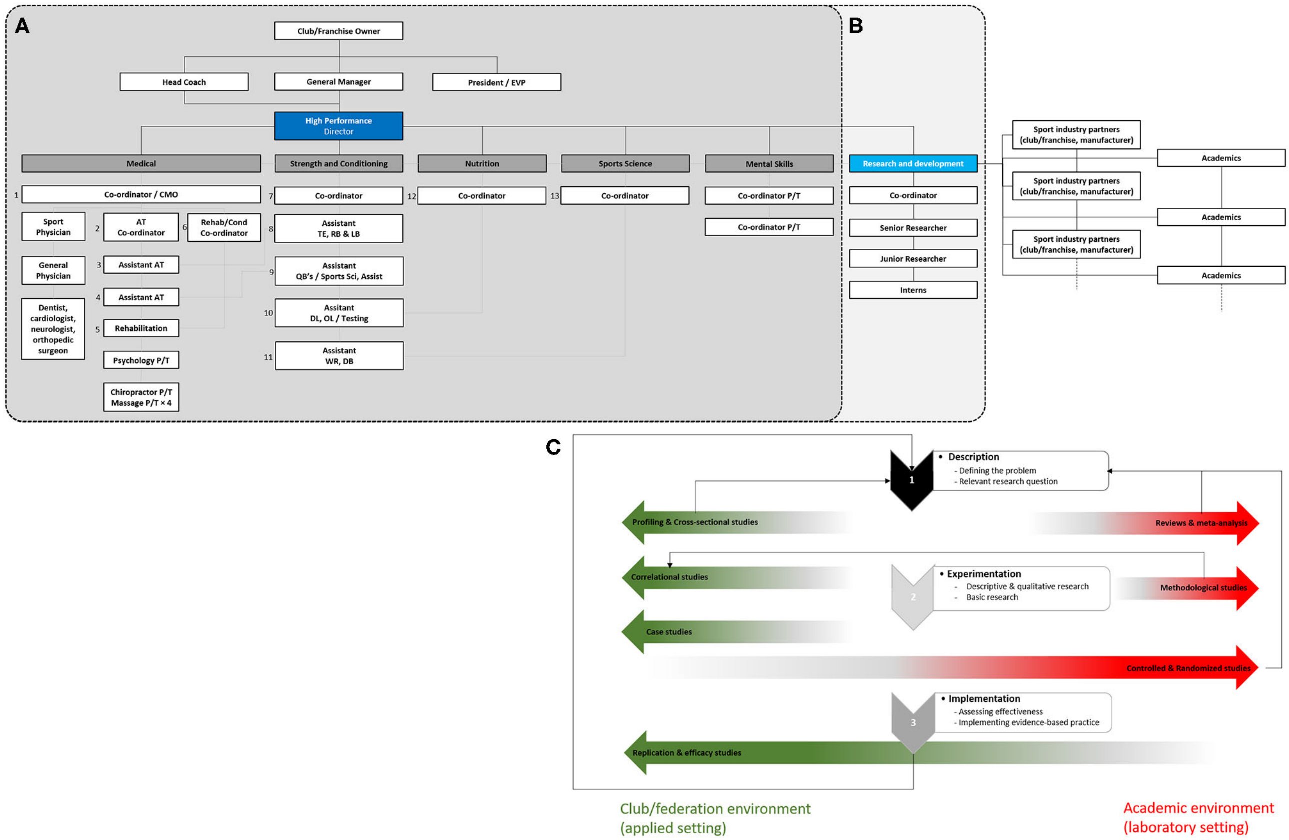

FIGURE 1 | The actual **(A)** and proposed **(B)** performance support model and its applied research process **(C)**. AT, athletic trainer; CMO, chief medical officer; DB, defensive back; DL, defensive line; EVP, executive vice president; LB, linebacker; OL, offensive line; P/T, physical therapist; QB, quarterback; RB, running back; TE, tight end; WR, wide receiver.

line of professional and elite sport in order to reinforce the necessary evolution of professional squads and federations to stay at the cutting edge of performance optimization.

INTEGRATION OF THE PERFORMANCE MODEL INTO TRADITIONAL SETTINGS

Modern professional and elite sport has gained an interest in creating athlete-centered structures (e.g., Boston Celtics Auerbach training center, Ultimate Fighting Championship's performance institute in Las Vegas, Aspire Academy in Doha, Chicago Cubs' Arizona spring training performance center, and Wrigley field high-performance facility), which include state-of-the-art sport science facilities and material for performance optimization. Because the margin between winning and losing is tiny (Davison et al., 2009), such environments take into account all the factors surrounding athlete's performance, health, and well-being.

In order to provide effective evidence-based, performance-oriented, and science-driven practices in sports science and sports medicine support, a positive integration is paramount, implying the organizational direction [i.e., owner, chief executive officers (CEOs), head coach, front office] to recognize and believe in the performance model and then favor the interaction between each department. As such, and because this has been reported to be a critical barrier (Fullagar et al., 2019), particular attention must be carried on ensuring that there is alignment between leadership/ownership and the performance team. This is especially ringing true on the "hands-on" staff (such as coaching, performance, and medical) that should view the overall picture of the organization culture and its performance model and develop coexistence and relationship based on different expertise enabling all staff. A clear holistic process with transparent roles and responsibilities facilitates decision-making regarding the somewhat paradoxal performance optimization and long-term health management (particularly relevant in youth elite sport environments) (Dijkstra et al., 2014).

However, problems may occur if groups within the club/federation are not open to new innovative ideas and scientific methodologies based on evidence-based practices to the optimization of player performance and health. Fixed mindsets not only create problems for the integration of the performance model (Nassis, 2017) but also may create silos between the performance departments and coaches/front office staff (Eisenmann, 2017; Drust, 2019). Clear goals and expectations with regard to where current practices are at the club/federation will help to plan the evolution of the *"here and now—winning today"* and the *"how do we maintain and sustain winning—success"*. If early adopter or innovator profiles would be helpful for compliance and acceptance (Nassis, 2017), in all cases, communication and time are keys to convince (unwilling) head coaches and organizational direction. However, because professional and elite sport setting is result-driven, time is lacking to install a confident working environment, where the worst scenario (i.e., losing consecutive matches) inevitably conducts to head coach eviction, thereby affecting the performance process (Drust, 2019).

In order to convince reluctant groups within the club/federation of the benefits from a sports science and sports medicine support model, the recruited performance director must have multiple strings to his/her bow. Based on our own experience, having a mix of practical (playing experience and/or backroom staff) and theoretical knowledge to ensure a clear understanding of the scientific prerequisite is a helpful asset to assist leaders such as the head coach (Bishop, 2008) by using similar language in a mutually respectful manner. In particular, having a scientific background at the postgraduate level (i.e., ideally having a postgraduate MSc or PhD qualification) would allow the identification (including discrediting poor/false research or pseudoscientific approaches) and adoption of effective evidence-based practices (e.g., targeting few identified areas having a meaningful impact on athletes' performance) that would directly and rapidly impact the decision-making process surrounding sport performance (Buchheit, 2016; Coutts, 2017; Nassis, 2017). Furthermore, such effective and easy to use innovative research-informed, practitioner-led interventions are more likely adopted than disruptive ones (Nassis, 2017) and would open doors for more cooperation. Besides agility and adaptability, additional leadership and interpersonal and communication skills would reinforce the communication needs (Eisenmann, 2017) and drive a centralized operating system that promotes the performance model and club/federation culture. As such, the performance director is the "gatekeeper" of the sports science and sports medicine services, ensuring optimal cooperation while avoiding confusion and pitfalls, notably through open paths of communication between staff.

REFINING THE PERFORMANCE MODEL

The rapid technological development (and its accompanying regulation adjustments) approved by most leading global sporting organizations, in addition to the increasing demand placed on the athletes, may highlight the important role of sports science and sports medicine staff in modern sport success (or failure). Alongside management leadership and acculturation (Jones et al., 2009), improving athletes' compliance for monitoring and evidence-based methodologies provides the opportunity to reinforce the use of specific devices and supporting strategies. For that, the shared decision-making process (i.e., including three key steps: choice, option, and decision) proposed in sports medicine (Dijkstra et al., 2017; Elwyn et al., 2017) may reduce conflict and participate as education mean for effective and succesful support.

The paradox in professional and elite sport setting is the different timelines requested to ensure key decisions (fast-working process) while promoting the best evidence-based practices (slow-working process) (Coutts, 2016, 2017; McCall et al., 2016). In this view, and because the director of performance may represent the cornerstone of the performance model and would have time for translational concept only, embedding a research and development (R&D) department (under the umbrella of performance director, **Figure 1B**) would be useful to provide scientific expertise in assessing long-term performance solutions and drive new ideas to improve the decision-making process for day-to-day servicing areas (Coutts, 2016, 2017; McCall et al., 2016; Eisenmann, 2017).

In fact, although developing research partnerships and innovation hubs (McCall et al., 2016) remains valid (see section *Reinforcing the Connection*), bringing researchers and their environment within the same organization is probably the most relevant way to bridge the gap between the "field and the lab" via the development of the triad "athlete–coach–researcher" (Sandbakk, 2018, 2019; Fullagar et al., 2019). Such club/franchise- (e.g., FC Barcelona in soccer, Chicago Cubs in baseball) or organization-embedded research (e.g., Australian, English, French, Norwegian institutes of sport) is generally considered to have greater impact on professional practice (Coutts, 2017). Relocating laboratories and researchers close to the field allows to better understand the constraints that may limit evidence-based practice translation (Bishop, 2008) to identify and conduct relevant ecologically valid applied researches (Reade et al., 2008a,b) that align with the "real-world" needs and perspectives (Jones et al., 2019). Improving the servicing resource with an R&D department would open doors for higher sports science and sports medicine research into applied practice (Fullagar et al., 2019) that may benefit higher education within (Bartlett and Drust, 2020) and outside professional and elite sport.

REINFORCING THE CONNECTION

Refining the performance model with the addition of an R&D department also allows to optimize collaboration with academics (McCall et al., 2016) or other infrastructures from the sport industry (e.g., R&D departments issued from the same or another sport/competition, equipment manufacturers). First, because research questions are established and prioritized by the R&D department (**Figures 1B,C**), thereby avoiding the common belief from many academics (much more than we think; part of those who believe that having practiced and/or coached at low levels equals head coaches' specific knowledge acquired over years) that head coaches are not sufficiently "brained" to share ideas. One may assume that some brilliant research findings emanated from innovation intuitively developed on the field by some head coaches. As such, adopting integrated knowledge translation models (Boland et al., 2020) involving practitioners in a research agenda would benefit end users through common concepts and vocabulary, the ability to link, exchange, and co-produce knowledge (participatory research, athlete engagement or involvement, and community-based research).

In professional and elite sport settings, proper controlled data collection allows a continuum between servicing and research (Halson et al., 2019) through implementation of intervention to verify a hypothesis (e.g., comparing two training methods). Instead of reinventing the wheel, the research iterative and bidirectional model proposed by Bishop (2008) remain topical. Profiling and cross-sectional studies easily implementable in "real-world" settings would provide values to reviews and meta-analyses to verify the problem identified (**Figure 1C**). Then, methodological and correlational studies are helpful to set the next steps. In addition, conducting qualitative research such as case study of one or few (elite) athletes (e.g., Brechbuhl et al., 2018; Solli et al., 2020) is one of the pathways bridging the gap between research and practice (Halperin, 2018). This may be an interesting "buy-in" strategy to create a working relationship between practitioners and head coaches (Halperin, 2018), which may result in mutual interests and more demanding research such as laboratory-based experiments (Fullagar et al., 2019). Bearing in mind that poor research (or associated approaches) would discredit all the efforts to support sports science and sports medicine, we believe that even difficult to implement parallel-group (e.g., Beard et al., 2019a,b) or crossover design (e.g., Sandbakk et al., 2015) with appropriate randomization remains possible and provides an opportunity to increase the quality of ecological research in the "real world" (Coutts, 2017; Fullagar et al., 2019). Replication studies must be considered at this stage if basic research has been already conducted. Finally, to truly have an impact on "real-world" settings, effectiveness trials, through replication and efficacy studies in ecological conditions, are imperative to improve quality decision in practice. Despite the reluctance of most journals for a "lack of novelty" (McLoughlin and Drummond, 2017; Nature, 2020), replicating experimental results with or without positive findings would be helpful for researchers and practitioners to decide whether a novel finding is real and large enough to have a practical impact. In this view, the recent coopetition (i.e., simultaneous cooperation and competition) proposal to merge performance data (Ramirez-Lopez et al., 2020) may also provide an alternative to improve sample size and ecological validity of applied research. Some organizations [e.g., FC Barçelona, Sacramento Kings, and Los Angeles Dodgers joint research on modeling players' decision (http://www.sloansportsconference.com/activities/research-papers/2019-research-paper-finalists-posters/) presented at the MIT Sloan Sports Analytics international conference] already take the plunge. Connecting with academics also means to be proactive in research grant application. As such, few initiatives get up. For example, last year, Paris Saint-Germain (PSG) and "Polytechnique" sponsored the "Sport analytics challenge" (https://www.agorize.com/en/challenges/xpsg) that allowed students to submit contributions or projects related to Opta data analysis using Python or R programming language aiming to increase PSG sporting performance. The winner received a 3-year thesis or postdoctoral fellowship (worth €100,000 including tax). Other research opportunities also arose from competition winning bid.

Similarly, major competitions such as the Olympic games often boost scientific support and research initiatives (Skibba et al., 2016), Paris 2024 being the last example with a call for elite sport-related scientific project from the French national agency for research. The flip side of the coin is that it fuels the lust of researchers who are out of sport context, increasing the risk of a setback from the head coaches for the interest of sports science and sports medicine. To avoid this and promote its catalyst effect, the funding stakeholders must carefully control the alignment of research project with its practical application in professional and elite sport setting.

CONCLUSION AND SUMMARIZING TIPS

The necessary evolution of professional and elite sport encompasses embracing better communication based on trust and mutual respect with head coach and management board/team, embedding an R&D department to relocate laboratories and researchers close to the field and reinforce their connection with the "real world" to promote best evidence-based, performance-oriented, and science-driven practices. In order to bridge the gap between research and practice and improve its impact on professional and elite sport setting, key considerations are summarized as follows:

- To improve collaboration with coaches/managers and athletes through
  - Creation of a pleasant work environment,
  - Proper communication (e.g., avoiding silos, eliminating segregation),
  - Rapid information dissemination that is meaningful for the different groups,
  - Staff development (e.g., workshop, newsletter),
  - Favor interaction and critical thinking inside and outside the box.
- To establish trust and building relationships with academics or other sports industry's infrastructures through
  - Integration of laboratory-based materials and researchers within the organization,
  - Development of "win–win" solutions (i.e., interesting and useful) promoting aligned inter- or multi-disciplinary research approach,
  - Improving education material and conferences involving scholars, scientists, practitioners, and/or coaches,
- To improve quality decision in practice through
  - Promotion of the best available evidence at the right time for the right athlete,

- Implementation of the "integration paradigm" whereby research guides practice, but practice also guides research,
- Guaranteeing stability, consistency of sports science and medicine support. This may require infrastructure's refinement to maintain effective communication.

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The authors listed have made substantial, direct and intellectual contribution to the work and approved it for publication.

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Sex and Age-Group Differences in Strength, Jump, Speed, Flexibility, and Endurance Performances of Swedish Elite Gymnasts Competing in TeamGym

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Purpose: To analyze sex and age group differences in strength, jump, speed, flexibility, and endurance performances of TeamGym athletes.

Methods: A total of 91 Swedish elite gymnasts (junior female, $n = 26$, age = 15.4 y; senior female, $n = 23$, age = 20.0 y; junior male, $n = 19$, age = 15.6 y; senior male, $n = 23$, age = 20.6 y) participated in three testing sessions on three separate days. These were: (1) a series of flexibility tests for the lower- and upper-body; (2) strength tests for the lower- and upper-body; and (3) various types of jumps, a 20-m sprint-run, and a 3,000-m run test.

Results: Males were 24% stronger in the back squat one-repetition maximum (relative to body mass) compared to females ($P < 0.001$, $H_g = 1.35$). In the pull-ups and dips, 2.4 and 2.3 times more repetitions were completed by the males compared to the females (both $P < 0.001$, $0.70 \leq R \leq 0.77$). However, females were similarly strong as males in the hanging sit-ups test ($P = 0.724$). The males jumped 29, 34, 33, and 17% higher in the squat jump (SJ), countermovement jump (CMJ), countermovement jump with arm swing (CMJa), and drop jump (DJ), respectively, compared to the females (all $P \leq 0.002$, $0.14 \leq \eta_p^2 \leq 0.60$). In the 20-m sprint run, males were 4% faster than females ($P < 0.001$, $R = 0.40$). Moreover, the females had significantly better flexibility than the males in the trunk forward bending, front split, and side split tests (all $P < 0.001$, $0.24 \leq \eta_p^2 \leq 0.54$). In the 3,000-m run test, males were 11% faster than females ($P < 0.001$, $\eta_p^2 \leq 0.54$). Compared to junior athletes, seniors performed better in the pull-ups, dips, SJ, CMJ, CMJa, and 20-m sprint-run tests (all $P \leq 0.012$, $0.31 \leq R \leq 0.56$, $0.16 \leq \eta_p^2 \leq 0.25$), with separate within-sex age-group differences (i.e., juniors vs. seniors) that were significant for the males but not for the females in the SJ, CMJ, CMJa, and 20-m sprint-run tests (males: all $P < 0.001$, $0.67 \leq R \leq 0.69$, $1.37 \leq H_g \leq 2.01$; females: all $P = 0.298$–732).

Conclusions: Large sex and age-group differences were observed for most physical performance metrics with specific within-sex age-group differences only observed for male athletes, with male seniors performing better than juniors in the SJ, CMJ, CMJa, and 20-m sprint-run tests.

Keywords: athletic performance, code of points, gymnastics, muscle strength, physical fitness, testing, gender

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INTRODUCTION

Gymnastics is a sport that combines characteristics of strength, explosive power, speed, and flexibility (Bale and Goodway, 1990; Bencke et al., 2002; Jemni et al., 2006) and is governed by the International Gymnastics Federation (FIG). One relatively new discipline of gymnastics is TeamGym, where a team of 8-10 participants competes in three apparatuses – the floor, tumbling, and trampette. Briefly, the TeamGym floor program involves choreography to music lasting between 2:15–2:45 min:s and includes flexibility movements, jumps, acrobatics, and balance elements. The tumbling routine comprises a tumbling track with a run-up of 16 m where the gymnasts perform series of acrobatic elements backward and forwards. The trampette routine uses a square-formed mini-trampoline with a 25-m run-up where the gymnasts perform somersaults with and without a vaulting table. All three routines require, in addition to physical fitness, high technical skills in acrobatic and gymnastic elements. A combined final score of the floor program and the three different rounds in the tumbling and trampette routines rank the team, applying the rules defined in the Code of Points which is reviewed and updated every four years (Sjöstrand et al., 2017). The performance level of TeamGym has increased rapidly based on the gradually enhanced difficulties from the first official European Championships in 2010 until the present day. This was likely related to the introduction of the 2010 years version of the Code of Points ranking system (Hughes et al., 2010) that was based on a new open-ended difficulty score, which has led to faster development of more advanced gymnastic elements. In addition, the regular updates of the Code of Points ranking system (every 4 years) have likely also had an impact on the performance characteristics of the sport. All these factors have possibly contributed to the increased physical and technical demands of elite-level TeamGym athletes.

FIG has testing and training programs for the other disciplines of gymnastics such as the age group development program for female artistic gymnastics for gradual evaluation of physical capacities and athletic development over time (Fink et al., 2015). Another testing program for artistic gymnastics is the functional measurement tool (Sleeper et al., 2012, 2016). However, there are no specifically developed testing and training programs for the TeamGym discipline. A TeamGym athlete is likely to benefit from having high explosive strength and maximal strength capacity especially in the lower body, which is very useful for rebounding from the floor and for vaulting during various types of somersaults (Hansen et al., 2019). Since a high run-up speed was found to be important for the performance score during various vaults in artistic gymnastics (Schärer et al., 2019), a high run-up speed is also likely to be related to the performance of the somersaults performed in TeamGym. As based on the performance characteristics of TeamGym and the data presented by Hansen et al. (2019), a test battery involving various maximal jumps, sprint running, and maximal strength tests might be of relevance for both physical profiling, as well as regular testing, of TeamGym athletes. Although the popularity of TeamGym is growing fast in Europe, research on this sport is still sparse, with most previous studies only addressing injury incidence/symptoms (Harringe et al., 2004, 2007; Lund and Myklebust, 2011). Currently, there is only one study that has detailed the physical fitness of senior TeamGym athletes where lower-body muscle function was evaluated using tests of vertical jump, linear sprint performance, and isometric leg press (Hansen et al., 2019). The results from that study showed moderate associations between mechanical lower-body muscle function and tumbling performance, as well as significant sex differences for almost all physical capacities.

Although the Code of Points has identical difficulty values for all elements of the routines in TeamGym for males and females, it is well known that males are taller and heavier than females and that males have greater maximal strength, explosive strength, sprinting speed, and endurance characteristics (Kraemer et al., 1989), while females are noticeably more flexible than males (Bale et al., 1992). Compared to females, males experience a more substantial increase in body mass and strength during the final years of adolescence, which may impact some physical abilities differently in the transition from junior to senior age (e.g., from an age of 15 to 20 years) in males vs. females (Kraemer et al., 1989; Handelsman, 2017). Moreover, sex differences in sports performance increase gradually after the age of 12–13 years and reach a plateau after the age of ∼20 years, which has been related to the rise in circulating testosterone due to puberty (Handelsman, 2017; Handelsman et al., 2018). The effect of pubertal age on sex-differences has also been shown to be relatively consistent for various types of physical abilities such as sprint running, middle-distance running, swimming, and handgrip strength (Handelsman, 2017). Maximal sprint ability is of substantial importance to performance in many sports with considerable sex differences commonly observed in senior athletes (Hansen et al., 2019; Nuell et al., 2019; Cardoso de Araújo et al., 2020). For instance, sex differences in sprint running have been attributed to the disparity in force/power and muscle volume characteristics (Nuell et al., 2019). In the study by Nuell et al. (2019), male senior sprinters had larger leg muscle volumes (especially in the hamstring muscle) and greater sprint mechanical properties than female sprinters which contributed to a 15% faster 80-m sprint time. Moreover, Askow et al. (2019) showed in a group of resistance-trained males and females (∼21 years of age), that males back squatted 30% more weight per kilogram of body mass than females. In a group of German Bundesliga soccer players, males were 11% faster in a 20-m linear sprint-run test and jumped ∼45% higher in the squat jump (SJ) and countermovement jump (CMJ) tests, when compared to females (Cardoso de Araújo et al., 2020). In a study conducted on Danish elite TeamGym athletes, Hansen et al. (2019) reported males to sprint 9% faster in a 25-m linear sprint-run test and to jump 24% higher in a CMJ test.

To date, there is no data available regarding sport-specific strength, jump, speed, flexibility, and endurance capabilities of elite-level TeamGym athletes and there is currently no data on how these abilities are characterized in different sex and age groups. Such information would be useful for optimizing training for athletic performance and to provide vital information for further updates to the Code of Points ranking system. Therefore, this study aimed to report the physical capacities of the best Swedish male and female TeamGym athletes at junior and senior levels as well as to analyze the effect of sex and age group (i.e., junior vs. senior athletes) on physical capacities. Based on a previous study by Hansen et al. (2019), we hypothesized that the senior males would jump ∼24% higher in the CMJ and run ∼9% faster in the 20-m sprint-run test than the senior females and that these sex differences would be higher for senior athletes (age of ∼20 years) than for junior athletes (age of ∼15 years), as based on previous findings by Handelsman (2017).

METHODS

Participants

Ninety-one elite-level gymnasts were recruited for this study including junior female ($n = 26$), senior female ($n = 23$), junior male ($n = 19$) and senior male ($n = 23$) athletes with the participant characteristics shown in **Table 1**. The study was performed according to the Declaration of Helsinki and had been pre-approved by the Swedish Ethical Review Board (#2019–06039). The inclusion criterion was that the athlete had been chosen for the first selection of the Swedish national team competing in TeamGym year 2020. The exclusion criteria were injuries and/or sickness that could affect the test results and/or pose a potential health risk for the athlete during testing. All participants received both written and verbal information about all the testing procedures and potential risks before they provided written informed consent.

Study Design

The first testing session started with flexibility assessments that took ∼20 min to complete for each participant with ∼2 min of rest in between the different tests. The second testing session was strength exercises that took ∼40 min to complete. This was followed by a third testing session including jumps, a 20-m linear sprint-run test, and a 3,000-m run test on a tartan track, which took ∼1.5 h to complete for each participant. The three testing sessions were performed on three separate days interspersed by ∼1 month between the first and second sessions and 4 days between the second and the third sessions. Before all testing sessions, the gymnast completed a 20-min structured warm-up and was informed to avoid hard physical activities 24 h before testing. The participants were well familiarized with all the different tests from previous years of training and testing.

Equipment and Measurements

Upon arrival at the laboratory, the gymnasts were asked about their amount of sport-specific training, which included gymnastics and strength training, reported as an average over the latest training year and expressed as a weekly training volume (i.e., hours per week). Stature was measured by using a standard wall stick scale and reported to the nearest millimeter. Body mass was measured barefooted and in light clothing with a Beurer BG 19 scale (Beurer GmbH, Ulm, Germany). The range of motion during the flexibility tests was assessed by measuring specific distances (described in detail below) with a standard tape measure reported to the nearest millimeter or centimeter depending on the current recommendations for the specific test. The jumping performances of the SJ, CMJ, and CMJ including a free arm swing (CMJa) were determined with an Opto Jump Microgate system (Microgate, Bolzano, Italy), which calculates jump height based on the flight time in the air during a jump (Glatthorn et al., 2011). A piece of similar equipment (IVAR Jump and sprint system, Spin Test, Tallinn, Estonia) was used to measure the drop jump (DJ), and the 20-m linear sprint-run performance (Carlsson et al., 2012). For all jump and sprint-run tests, the gymnast performed three repetitions in each test with the best result being reported.

Detailed Information About the Testing Procedure

The test battery was developed from former testing procedures in other disciplines of gymnastics and different sports with similar demands. The strength, jump, speed, and 3,000-m run tests were performed according to "Fysprofilen[1]", which is a test battery developed by the Swedish Olympic Committee, that is frequently used for assessment of different qualities of physical performance in Swedish elite athletes. The flexibility tests were based on standard testing procedures that are commonly used in other gymnastic disciplines such as artistic gymnastics (Sleeper et al., 2012, 2016; Fink et al., 2015).

Flexibility Tests

The dorsiflexion lunge test for the right and left foot

To assess ankle dorsiflexion, the participant placed one foot and both hands against a wall where after the knee was lunged toward the wall. The foot was then progressively moved away from the wall until the maximum range of dorsiflexion was reached (**Figure 1A**). During the lunge, the test leader held the heel to prevent it from lifting from the floor, with the knee in contact with the wall and with the tibia advancing over the talus into maximum dorsiflexion. The distance was measured from the wall to the participant's hallux with distance reported to the nearest millimeter.

The shoulder flexibility test

The shoulder flexibility was tested with the participant lying in a prone position with the stomach, chin, and nose in contact with the floor. Both arms were held straight and parallel to the body and flexed to 180°. The gymnast held a wooden dowel pin using an overhand grip with the wrist in a neutral position and with the thumbs touching each other where a maximal shoulder flexion with extended elbows was performed (**Figure 1B**). The distance was recorded from the floor to the dowel pin where the thumbs touched each other, to the nearest 0.5 cm (Sleeper et al., 2012). The distance was reported as positive (i.e., with more positive meaning more flexible).

The trunk forward bending test

The test was conducted with the participant standing on a bench with the feet together and with straight legs holding a wooden dowel pin by using an overhand grip while keeping the wrists in a neutral position and the thumbs touching each other. From this

[1]Fysprofilen (2016). Available at: https://fysprofilen.se/sv/default.aspx?PageID=1142.

TABLE 1 | Participant characteristics for junior female (n = 26), senior female (n = 23), junior male (n = 19), and senior male (n = 23) TeamGym athletes presented as mean ± standard deviation (SD) with the exception for training time that is presented as median and interquartile range.

		Females	Males	Combined	Test statistic	*P*-value	ES
Age (years)	J	15.4 ± 0.9	15.6 ± 0.8	15.5 ± 0.9	-	–	–
	S	20.0 ± 3.0	20.6 ± 3.2	20.3 ± 3.1	-	–	–
Body height (cm)	J	163.3 ± 5.8	174.3 ± 5.3	167.9 ± 7.8	$^{\#}F_{1,87} = 109.0$	<0.001	0.56
	S	163.8 ± 4.9	176.1 ± 5.1	170.0 ± 7.9	$^{\$}F_{1,87} = 1.2$	0.282	0.01
					$^{£}F_{1,87} = 0.3$	0.561	0.00
BM (kg)	J	57.8 ± 6.3	65.7 ± 7.1*§	61.1 ± 7.7	$^{\#}F_{1,87} = 69.0$	<0.001	0.44
	S	59.4 ± 6.5	74.9 ± 6.9	67.2 ± 10.3	$^{\$}F_{1,87} = 14.9$	<0.001	0.15
					$^{£}F_{1,87} = 7.3$	0.008	0.08
BMI (kg·m^{-2})	J	21.6 ± 1.5	21.6 ± 2.1*§§	21.6 ± 1.8	$^{\#}F_{1,87} = 7.9$	0.006	0.08
	S	22.1 ± 1.8	24.1 ± 1.3	23.1 ± 1.9	$^{\$}F_{1,87} = 17.2$	<0.001	0.16
					$^{£}F_{1,87} = 8.1$	0.006	0.09
Training volume (h·week^{-1})	J	13 (12–15)	14 (12–16)	13 (12–15)	$^{\#}U = 949$	0.519	–0.07
	S	14 (14–15)	15 (14–17)	15 (14–16)	$^{\$}U = 738$	0.017	–0.25

*BM, body mass; BMI, body mass index; J, juniors; S, seniors. F-values, P-values, and effect sizes (ES), partial eta squared effect size (η_p^2), were obtained by a two-way ANOVA. # Main effect for sex. \$ Main effect for age group. £ Main effect for interaction between sex and age group. In case of a significant interaction effect, a within-sex-group comparison of J vs. S was performed with an independent t-test. For training time, U-values, P-values, and effect sizes (R) were obtained by a Mann-Whitney U-test. *§ significantly different from male seniors (P < 0.001, Hedges' g effect size [H_g] = –1.29). *§§ significantly different from male seniors (P < 0.001, H_g = –1.43).*

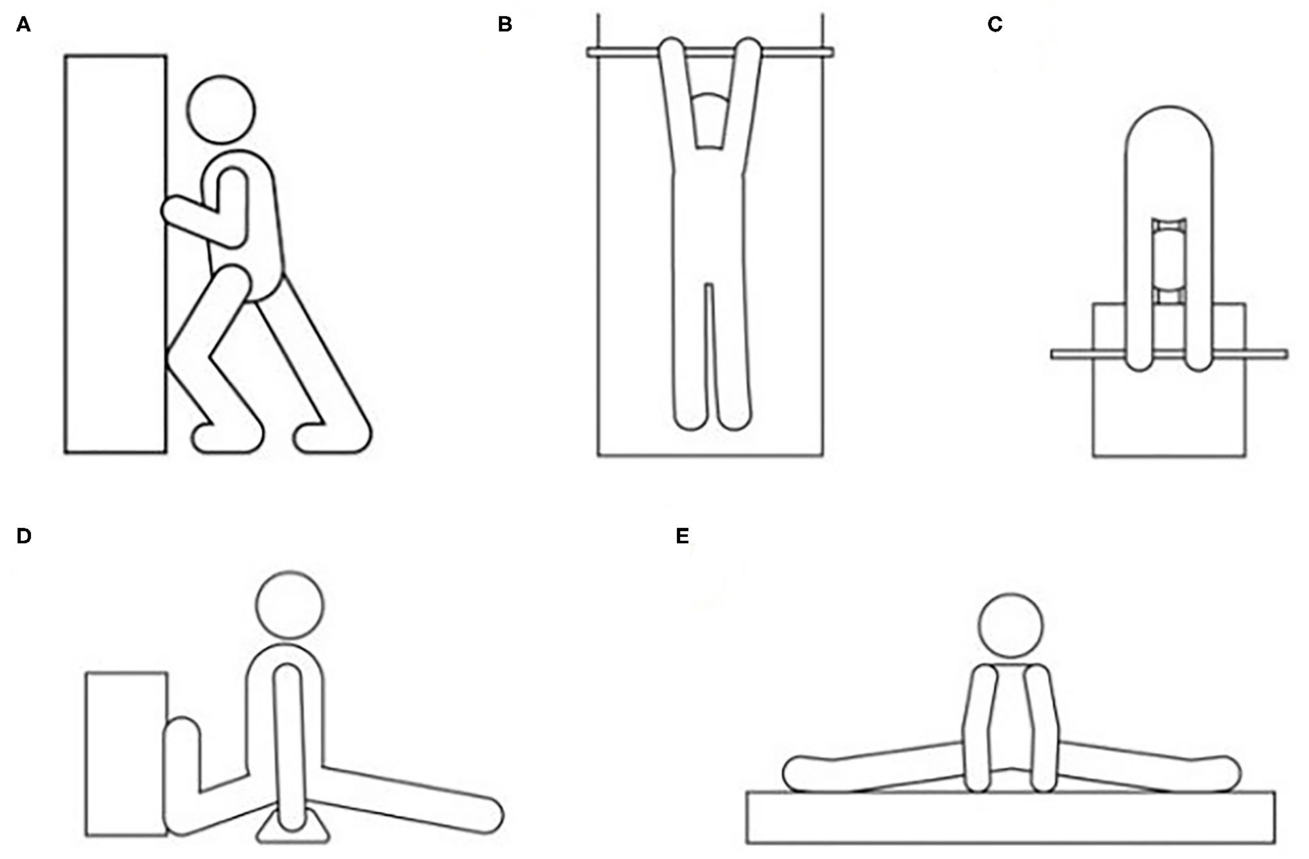

FIGURE 1 | The figure describes how the flexibility tests were performed with: **(A)**, the dorsiflexion lunge test for the right and left foot; **(B)**, the shoulder flexibility test; **(C)**, the trunk forward bending test; **(D)**, the front split test for the right and left legs; and **(E)**, the side split test.

starting position, the participant bent forward and tried to come as close to the floor as possible (**Figure 1C**). The distance was recorded from the top of the bench to the dowel pin where the thumbs touched each other, to the nearest 0.5 cm. The distance under and over the bench was defined as positive and negative, respectively (Fink et al., 2015).

The front split test for the right and left leg

The participant performed the right front split with the left hip extended maximally and the right hip flexed maximally (vice versa for the left front split). The tibia of the left leg was placed against the wall vertically where after the participant was instructed to slide out into a split position. During the test, the back had to be vertically positioned to the hip with shoulders parallel to the wall (**Figure 1D**). To maintain a proper testing position, the participant was permitted to use floor parallel bars and with the test leader fixating the back foot for maintaining the tibia in a vertical position. The measurement of the distance was from the floor to the highest point of the perineal area and reported to the nearest 0.5 cm and reported as negative units (i.e., the less flexible the more negative score). If the participant maintained the split with full contact with the floor, the result was 0 cm (Sleeper et al., 2012).

The side split test

The participant started the test with the heels placed perpendicular to a straight line before performing a slide-out to a side split (both hips abducted maximally). At the same time, the participant leaned forward and placed both hands in front of the body (**Figure 1E**). The measurement was performed in front of the participant, from the floor to the highest point of the perineal area, and reported to the nearest 0.5 cm and in negative units. If the participant had full contact with the floor, the result was 0 cm (Sleeper et al., 2012).

All flexibility tests were conducted in the same order as reported in the text above and the participant had ∼2 min of rest in between tests.

Strength Tests

The back-squat test

The purpose of this test was to evaluate the maximal strength of the lower body with the back squat exercise while measuring the maximum weight lifted once (1 RM) (Levinger et al., 2009). This test was a free weight exercise with a men's Olympic barbell (20 kg) placed on the shoulders behind the neck. From a standing position, the participant performed a controlled knee flexion until the thighs were parallel to the floor and then extended the knees back to the starting position. Each participant completed the tests with the following load increase: (1) five repetitions at 50% of estimated 1 RM; (2) three repetitions at 80% of estimated 1 RM; and (3) one repetition at 90% of estimated 1 RM. The result was presented as strength relative to body mass (i.e., total lifted weight [kg]/body mass [kg]). This test was only performed by the seniors (i.e., participants aged $\geq$ 18 years, or being 17 years turning 18 years within the specific year) as some of the younger junior athletes had no adequate experience of lifting technique training, and the technique was, therefore, considered to be insufficient according to the prescribed guidelines for 1 RM testing of youths (Faigenbaum et al., 2009). The back-squat test was performed by 21 senior females and 23 senior males.

The pull-up test

In this test, the participant was freely hanging from a barbell using an overhand grip at shoulder-width. The participant then performed a pull-up until the chin was horizontal to the barbell, followed by a lowering back to the starting position. The participant completed as many repetitions as possible without any break in between repetitions with the result being the maximum number of approved repetitions. A repetition was only approved if the gymnast had the chin at the level of the barbell, without kipping with the body and/or legs or changing the handgrip.

The dips test

This test was performed on two handles with the participant starting with straight arms at a shoulder-width position. The body was lowered until the back of the upper arm (i.e., triceps) was parallel to the floor, followed by an arm push-up back to the starting position. The participant completed as many repetitions as possible without any break in between repetitions with the result being the maximum number of approved repetitions.

The hanging sit-ups test

The test started with the participant hanging upside down from a bar in a position where the knees were fixed at a 90° knee joint angle using an inverted sit-up station. In the starting position, the gymnast hanged upside down with the whole back in contact with the backrest while holding a folded cotton band behind the neck where after the upper body was raised until the elbows touched the knees and returning to the starting position in a controlled movement (Harris et al., 2015). The participant performed as many repetitions as possible without any break in between repetitions with the result being the maximum number of approved repetitions.

All strength tests were conducted in the same order as reported in the text above and the participant had ∼5 min of rest in between tests.

Jump, Sprint, and Endurance Tests

The SJ test

This test was performed as a maximum vertical jump from ∼90° knee-joint flexion with a standstill of ∼2–3 s, the feet placed at hip-width and the hands placed on the hips. The SJ test was approved when the participant, on the test leader's command and without countermovement, jumped as high as possible with a full extension of the hip- and knee joints and with take-off and landing at approximately the same spot on the floor [for more details see Markovic et al. (2004)].

The CMJ test

This test was performed as a maximum vertical jump starting from an upright standing position, with the feet placed at hip-width apart and with the hands placed on the hips. The jump was initiated with a quick squat to a self-selected knee joint angle that was followed by a maximal explosive jump. During the flight phase, the gymnast had to maintain a full extension of the hip- and knee joints, with take-off and landing at approximately the same spot on the floor [for more details see Markovic et al. (2004)].

The CMJa test

The test started with a quick squat to a self-selected knee-joint angle followed by an explosive jump while including a supporting arm swing. During the flight phase, the gymnast had to maintain a full extension of the hip and knee joints and the take-off and landing had to be at approximately the same spot on the floor. In comparison to a CMJ test, the CMJa test incorporates the coordination qualities of arms and legs (Cheng et al., 2008).

The DJ test

The test started with a step-out from an elevated platform with a drop onto the ground followed by an immediate maximal vertical response jump. The DJ was performed from two different heights, 20 and 40 cm, respectively. These heights were chosen based on previous training and testing routines. The participant was informed to have the shortest possible contact time and to jump as high as possible. Jump height (cm) and contact time (ms) were registered together with a reactive strength index (i.e., the dynamic explosive vertical jump capacity) calculated as the optimal fall height, i.e., the best result from the 20 or 40 cm platform heights multiplied by 10 and divided by contact time.

The 20-m linear sprint-run test

The participant started the test from a split stance position 50 cm behind the first photocell. Split times at 5 and 10 m, as well as the end time after 20 m, were recorded to the nearest 0.01 s. Prior to the test, the gymnast performed two 20-m sprint runs at ∼80% of maximum speed, followed by ∼5 min of passive rest before the test.

The 3,000-m run test

After ∼5 min of warm-up running at a low-to-moderate intensity and a passive rest of ∼5 min, a 3,000-m run test was completed. The participant was informed to complete the test as fast as possible. The test was performed on an indoor 200-m tartan track and was a modified version of the Cooper test (Cooper, 1968). The participant's time to complete the test was measured with a stopwatch and immediately after the test, the athlete rated his/her level of perceived exertion using the 6-20 rating of perceived exertion (RPE) scale (Borg, 1982). The 3,000-m run test was performed by 14 junior females, 19 senior females, 14 junior males, and 13 senior males.

All the included tests in the third testing session were conducted in the same order as reported in the text above. The third testing session took ∼1.5 h to perform and the participants had ∼10 min of rest in between jumps, sprints, and the 3,000-m run test.

Statistics

A statistical power calculation was performed *a priori* using data from a previous study (Hansen et al., 2019), and unpublished data on Swedish junior and senior TeamGym athletes were used to assume the magnitude of the differences between sex and age-groups. For a power "cut-off" of 0.80 and an alpha level of 0.05, a minimum sample size of ∼14 participants within each of the two age-groups was required (i.e., a minimum sample of 28 females and 28 males). The data was processed in Microsoft Excel 2019 (Microsoft Armonk, New York, USA) with statistical analyses performed in the Statistical Package for the Social Sciences (SPSS 21, IBM Corp, Redmond, Washington, USA) with the level of significance set at $\alpha = 0.05$. The distribution of data was evaluated by visual inspection of Q–Q plots and histograms together with the Shapiro-Wilks analysis. Parametric tests were used for normally distributed data whereas non-parametric alternative tests were used for non-normally distributed data. Normally distributed data are presented as the mean ± standard deviation (SD) while non-normally distributed data, as well as ordinal data, are presented as the median and interquartile range (IQR). A two-way univariate ANOVA was used to analyze the main effects of sex and age group, as well as the interaction effect between sex and age group. In case of a significant interaction effect, a *post-hoc* independent t-test was used to compare juniors vs. seniors within each sex group with only significant results being reported. For skewed data or ordinal data, a Mann-Whitney U-test was used to analyze the main effects of sex and age group. In addition, an analysis of juniors and seniors within each sex group was performed with a Mann-Whitney U-test, with only significant results being reported. For the independent t-tests, the standardized mean difference (Hedges' g effect size [H_g]) was computed according to the equations presented by Lakens (2013) and interpreted as small ($H_g = 0.2$), medium ($H_g = 0.5$), and large ($H_g = 0.8$). For the Mann-Whitney U-test, the R effect size was reported and calculated as the z value divided by the square root of the number of observations (i.e., n). The effect size for the ANOVA tests was presented as partial eta squared (η_p^2).

RESULTS

The anthropometrical characteristics are displayed in **Table 1**. The male athletes were, in comparison to the female athletes, 7% taller and 21% heavier which resulted in a body mass index (BMI) that was 5% higher. Senior compared to junior athletes (as both sexes combined) possessed a similar body height but were 10% heavier with a 7% higher BMI. This difference between age groups was mainly due to the substantially higher body mass (14%) and BMI (11%) for male senior vs. junior athletes as indicated by the significant interaction effects of sex on age group. In addition, significant differences in body mass and BMI between age groups were observed for the males with no such differences for the females. The training volume was significantly higher for seniors compared to juniors (15 vs. 13 $h \cdot week^{-1}$) with no significant differences between the sexes.

The results from the strength tests are demonstrated in **Figures 2A–C** and show that the males were substantially stronger than the females in the pull-ups and dips exercises whereas there was no difference between the sexes for hanging sit-ups. Both female and male seniors were stronger than juniors in the pull-ups and dips exercises, while there was no effect of age group on the results for the hanging sit-ups. The back-squat strength ratio (i.e., the lifted weight divided by body mass) was

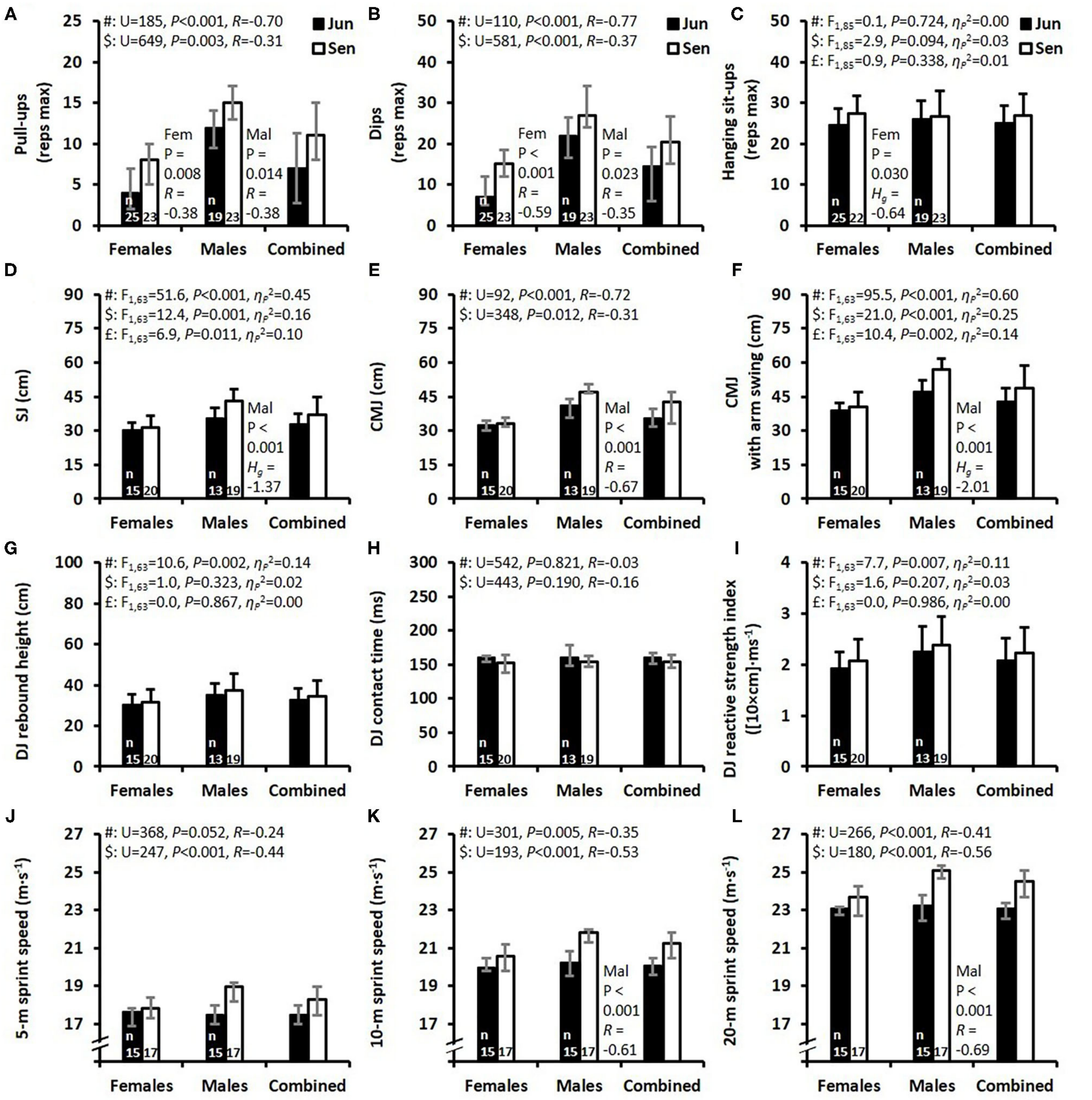

FIGURE 2 | Results for the strength **(A–C)**, jumping **(D–I)**, and running sprint **(J-L)** performances presented as mean ± SD **(C,D,F,G,I)** and as median and interquartile range **(A,B,E,H,J–L)** for the junior (Jun) and senior (Sen) female and male athletes and the combined group of female and male athletes. Abbreviations: SJ, squat jump; CMJ, countermovement jump; DJ, drop jump; reps max, the maximum number of repetitions; Fem, females; Mal, males; Hg, Hedges' g effect size. F-values, P-values, and partial eta squared effect size (η_p^2), were obtained by a two-way ANOVA. #Main effect of sex. $Main effect of age group. £Main effect for interaction between sex and age group. In case of a significant interaction effect, a within-sex-group comparison of Jun vs. Sen was performed with an independent *t*-test **(D,F)** with significant results being reported. In **(A,B,E,H,J–L)**, *P*-values were obtained with a Mann-Whitney U-test presented together with an R effect size, and separate within-sex-group comparisons between juniors and seniors were performed using a Mann-Whitney *U*-test with significant results being reported. The numbers located at the bottom of each of the four bars indicate the number of participants (*n*) in the specific test.

1.44 ± 0.17 and 1.79 ± 0.31 for the female and male seniors, respectively ($P < 0.001$, $H_g = -1.35$). The results for the SJ, CMJ, and CMJa tests are displayed in **Figures 2D–F** which show main effects of sex, age group, as well as an interaction effect between sex and age group with substantially larger differences between junior and senior males than between junior and senior females.

The results from the DJ test are displayed in **Figures 2G–I** which show that the DJ rebound height and DJ reactive strength index were higher for the male athletes, with no difference between sexes in DJ contact time, and with no statistical main effect of age group for all DJ variables.

The average speeds for the first 5 and 10 m of the 20-m linear sprint-run test, as well as finishing time at 20 m, are shown in **Figures 2J–L** which demonstrates that males were significantly faster over 10 and 20 m compared to the females. The juniors combined were also significantly slower than the seniors at 5, 10, and 20 m. The male juniors were significantly slower than the male seniors at 10 and 20 m whereas the female juniors and seniors were similarly fast at 5, 10, and 20 m. The corresponding median (IQR) times at 5 m were 1.02 (1.01–1.07), 1.01 (0.98–1.04), 1.03 (1.00–1.06), 0.95 (0.94–0.99) s for the female juniors, female seniors, male juniors, and male seniors, respectively (main effect of sex: $U = 368$, $P = 0.052$, $R = -0.24$; main effect of age group: $U = 247$, $P < 0.001$, $R = -0.44$). The separate comparisons between juniors and seniors within each sex group demonstrated no significant differences. The corresponding times at 10 m were 1.80 (1.76–1.82), 1.75 (1.70–1.82), 1.78 (1.73–1.85), 1.65 (1.64–1.69) s for the female juniors, female seniors, male juniors, and male seniors, respectively (main effect of sex: $U = 301$, $P = 0.005$, $R = -0.35$; main effect of age group: $U = 193$, $P < 0.001$, $R = -0.53$). The separate comparisons between juniors and seniors within each sex group demonstrated significant differences for the male juniors vs. seniors ($P < 0.001$, $R = -0.61$) but with no difference for the female juniors vs. seniors. The corresponding finish times of the 20-m sprint run were 3.12 (3.11–3.17), 3.04 (2.97–3.17), 3.10 (3.03–3.21), 2.87 (2.84–2.92) s for the female juniors, female seniors, male juniors, and male seniors, respectively (main effect of sex: $U = 266$, $P < 0.001$, $R = -0.41$; main effect of age group: $U = 180$, $P < 0.001$, $R = -0.56$). Similar to the 10 m split time, the comparison between juniors and seniors within each sex group revealed a significant difference between male juniors and seniors ($P < 0.001$, $R = -0.69$), with no significant difference between the female junior and senior groups.

The flexibility test results that are shown in **Figures 3A–F** reveal that the females were significantly more flexible than the males in the trunk forward bending, front split, and side split tests (**Figures 3D–F**), but similarly flexible in the dorsiflexion lunge test (**Figure 3A**). However, the males scored higher flexibility in the shoulder flexion test than the females, but this difference was not significant (**Figure 3C**). All flexibility tests revealed no significant age group effects. The dorsiflexion lunge side difference (i.e., the difference between the most and least flexible legs) showed no main effects of sex or age group (**Figure 3B**). The difference (as median and IQR) between the most and least flexible legs during the front split was 5.0 (1.6–8.0), 5.0 (1.0–7.0), 3.0 (1.5–9.0), and 2.0 (1.0-6.8) cm for the female juniors, female seniors, male juniors, and male seniors, respectively (main effect of sex: $U = 965$, $P = 0.607$, $R = -0.05$; main effect of age group: $U = 895$, $P = 0.265$, $R = -0.12$). The separate comparisons between age groups within each sex revealed no significant differences.

The 3,000-m run test was completed in 15.5 ± 1.6, 14.8 ± 1.1, 13.5 ± 1.2, and 13.4 ± 1.2 min for the female juniors, female seniors, male juniors, and male seniors, respectively, with a significant main effect of sex, but no significant main effect of age group or interaction between sex and age group (sex: $F_{1,56} = 25.7$, $P < 0.001$, $\eta_p^2 = 0.31$; age group: $F_{1,56} = 1.6$, $P = 0.206$, $\eta_p^2 = 0.03$; interaction: $F_{1,56} = 0.7$, $P = 0.395$, $\eta_p^2 = 0.01$). The RPE immediately after the 3,000-m test was similar for female juniors (18 [16–19]), female seniors (18 [18–19]), male juniors (18 [17–19]), and male seniors (17 [16–18]) (main effect of sex: $U = 329$, $P = 0.077$, $R = -0.23$; main effect of age group: $U = 407$, $P = 0.529$, $R = -0.08$). Separate comparisons between juniors and seniors within each sex group revealed no significant differences in RPE. All the strength, jump, speed, endurance, and flexibility results can also be found in the **Supplementary Tables**.

DISCUSSION

This study aimed to describe the physical capacity of Swedish elite TeamGym athletes and to analyze sex differences, as well as compare junior with senior athletes. The results showed large sex differences in most of the physical performance parameters. The males were substantially stronger, jumped higher, sprinted faster, and had better endurance performance. The senior athletes performed, in comparison to the junior athletes, better in the pull-ups, dips, SJ, CMJ, CMJa, and 20-m sprint-run. However, sex-specific age-group comparisons for the SJ, CMJ, CMJa, and 20-m sprint-run tests revealed larger age-group effects in males than in females.

The results of sex differences observed in the current study align with previous findings that males are taller and heavier than females, and have greater maximal strength, vertical jump performance, sprinting speed, and endurance characteristics (Bishop et al., 1987; Bale et al., 1992; McMahon et al., 2017; Cardoso de Araújo et al., 2020). In comparison, females are significantly more flexible than males (Bale et al., 1992). To our knowledge, there is only one previous study that has analyzed the performance characteristics of elite TeamGym athletes (Hansen et al., 2019). We hypothesized, based on the latter study, that sex differences for the CMJ and the 20-m sprint run would be ∼24% and ∼9%, respectively. However, in the current study, the males jumped 34% higher than the females in the CMJ and the males completed the 20-m sprint run in 4% less time than the females. The substantially lower sex difference observed for the 20-m sprint, when compared to the CMJ, was unexpected, since moderate to very large correlations between 20-m sprint and CMJ performances have been observed previously in different groups of soccer players (Haugen et al., 2012). Haugen et al. (2012) also noticed that some equally fast athletes could vary by as much as 10–12 cm in a CMJ which indicates that different physiological and biomechanical factors are related to horizontal acceleration (i.e., sprinting) and vertical acceleration (i.e., jumping). However, as both factors appear to be important for TeamGym performance (Hansen et al., 2019; Schärer et al., 2019), athletes with better sprint skills may compensate for lower jump performance. The somewhat divergent findings observed for the sprint and jump performances in this study when compared to both our hypothesis and the study by Hansen et al.

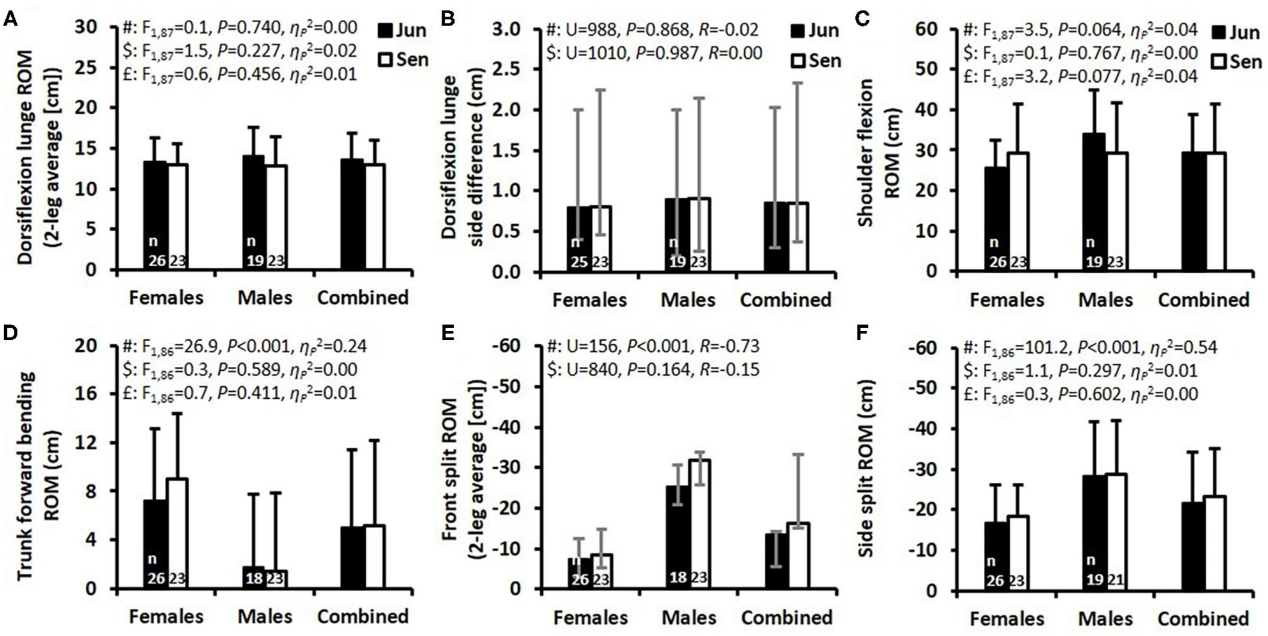

FIGURE 3 | Flexibility test results presented as mean ± standard deviation (SD) **(A,C,D,F)** and as median and interquartile range **(B,E)** for the junior (Jun) and senior (Sen) female and male athletes and the combined group of female and male athletes. Abbreviations: ROM, range of motion; Hg, Hedges' g effect size. *F*-values, *P*-values, and partial eta squared effect size (η_p^2), were obtained by a two-way ANOVA. #Main effect of sex. $Main effect of age group. £Main effect for interaction between sex and age group. In **(B,E)**, *P*-values were obtained by a Mann-Whitney U-test presented together with an R effect size. The numbers located at the bottom of each of the four bars indicate the number of participants (*n*) in the specific test.

(2019) may be due to different athletic populations, where the current study assessed Swedish elite gymnasts recruited from the first selection of the national team, whereas Hansen et al. (2019) instead tested the final national team.

In the current study, the SJ, CMJ, and CMJa jump heights were lower for junior compared to senior athletes (for both sexes combined, on average ∼12% lower) and the 20-m linear sprint-run was 5% slower for junior vs. senior athletes (3.13 s vs. 2.97 s). This was not surprising, as physical ability and sports performance are known to increase during adolescence (Handelsman, 2017), and therefore may partly explain such findings. However, as shown in **Figure 2**, these differences were mainly manifested in the male athletes as confirmed by the significant interaction effects between sex and age group. Separate age-group comparisons within each sex group revealed significant differences only between male juniors vs. seniors. This may be due to the substantial increase in muscle mass and strength observed during male adolescence, and the resultant divergence in physical ability and sports performance between the sexes, from puberty until ∼20 years (Kraemer et al., 1989; Handelsman, 2017). For both age groups combined, the males jumped 29% higher in the SJ and 34% higher in both the CMJ and CMJa than the females. The somewhat larger sex difference for the two jumps that involved a countermovement indicates that the males were slightly more effective in utilizing the stretch-shortening cycle (Ziv and Lidor, 2010) and/or involving the hip extensor muscles (Lees et al., 2004) in the CMJ and CMJa than the females. In addition, the DJ height and DJ reactive strength index were both ∼17% higher for the males vs. the females, which indicate, together with previous findings (Prieske et al., 2017), that males probably have better vertical leg stiffness and, thus, probably are better at utilizing the stretch-shortening cycle (Kipp et al., 2018).

Moreover, gymnasts are in general known for their high strength relative to body mass (Bale and Goodway, 1990), which was also confirmed in the current study as the 1 RM back-squat strength relative to body mass demonstrated higher values for both sexes compared to basketball players, and for males, a similar strength level to elite rugby players (Tanner and Gore, 2013). Although lower body strength is likely to be more important than upper body strength in TeamGym athletes, a sufficient level of upper-body strength is also likely to be important. In the current study, sex and age-group differences were found for the pull-ups and dips. However, the sex-specific differences between age groups were similar which was contrary to the results for the 20-m sprint run and the jump tests (SJ, CMJ, and CMJa). A potential explanation for this finding could be related to a combination of how TeamGym athletes train and respond to strength training as well as where they gain muscle during puberty. It can be noted that the male senior athletes were considerably heavier than the male junior athletes whereas no such difference was revealed in the female athletes.

The flexibility demands of TeamGym have increased since the latest update of the Code of Points in 2017 and the level of the floor routine elements has increased on a year-to-year basis, which puts higher demands on flexibility. The sport of gymnastics has always been characterized by high flexibility requirements, and indeed flexibility has been a critical component that separates gymnastics from other sports (Bale and Goodway, 1990). For TeamGym, the importance of this factor has substantially increased with the latest update of the Code of Points. The hip flexibility is likely to be of specific importance to TeamGym athletes, which is similar to the other gymnastic disciplines (Bale and Goodway, 1990). Since the current study showed males to be substantially less flexible than the females in the trunk forward bending, front split, and side split; male TeamGym athletes should potentially emphasize hip flexibility training more than their female counterparts.

The maximal aerobic power in artistic gymnastics has been studied for many years with maximal oxygen uptakes in a combined group of males and females reported to ~50 ml·kg^{-1}·min^{-1} (Jemni et al., 2006). Therefore, it is logical to conclude that a gymnast needs a maximal oxygen uptake that is fairly similar to the value of a healthy female or male individual of the same age (Andersen et al., 1987; Aspenes et al., 2011). Although maximal oxygen uptake is probably not a direct key performance indicator in the performance of TeamGym, a sufficient level is probably important for optimal recovery from training and cardiovascular health (Carey et al., 2007; Aspenes et al., 2011). The 3,000-m run test result can be used to roughly evaluate the cardiovascular fitness of the gymnast since the more traditional 12-min run test introduced by Cooper (1968) has been used as a surrogate marker of cardiovascular fitness (Bandyopadhyay, 2015). As based on the 3,000-m run performances in the current study, average maximal oxygen uptakes for male and female TeamGym athletes were estimated as 42 and 49 ml·kg^{-1}·min^{-1}, respectively, and are fairly similar to values reported in previous studies for similar age groups from the general population (Andersen et al., 1987; Aspenes et al., 2011). However, the estimated values are likely to be slightly lower than the true values since the estimation was based on a 12-min distance (Bandyopadhyay, 2015) as calculated from the 3,000-m speeds; this is because the average completion time for the 3,000-m test was 14.4 min, i.e., higher than 12 min.

Compared to other elite team-sport athletes (futsal, handball, football, rugby), the TeamGym athletes in the current study showed ~5% higher vertical jump (SJ and CMJ) performances (Loturco et al., 2018) and seem to have higher sprinting and acceleration abilities compared to netball, tennis, cricket and basketball players, but similar sprinting and acceleration abilities as elite football players (Tanner and Gore, 2013). This data indicates that a high maximal sprinting speed for the run-up is important in TeamGym. Moreover, force impulse generation during the jump phase seems to be essential for successful performance. Gymnasts with high eccentric and concentric strength and explosive capacities can produce high force impulse and momentum; factors that likely contribute to more advanced acrobatics (French et al., 2004). It has been shown that resistance strength training programs in gymnastics can increase the force impulse in the CMJ and SJ tests, which enable gymnasts to jump higher and to perform better-scoring gymnastic acrobatic elements, mainly due to the increased flight time (French et al., 2004). The combination of an eccentric muscle action followed by fast concentric muscle action is described as the stretch-shortening cycle, which is a predictor of sprint capacity and high-speed movements in general (Komi, 2000). In this study, we used different jumps such as CMJ, CMJa, SJ, and DJ to evaluate the gymnast's potential to produce force via the lower body, which is very likely to influence the performance in TeamGym. In TeamGym, it is important to generate a high speed and thus forward momentum due to the long run-up in two of three apparatuses. In comparison, artistic gymnastic only requires a run-up for one of several apparatuses. Furthermore, a high run-up speed is correlated with the difficulty score in the vault in artistic gymnastics (Schärer et al., 2019). Due to this, a high run-up speed is likely to be more important to overall performance in TeamGym than in artistic gymnastics.

The sport of TeamGym has a lower focus on weight-bearing exercises compared to artistic gymnastics and involves the use of more rebounding equipment, where a longer contact time with the equipment enables a longer time for force-impulse generation. Such factors could describe, as compared to earlier findings, that our group of male TeamGym athletes was taller and heavier compared to athletes of similar age competing in artistic gymnastics (Jemni et al., 2006). The same logic applies to the female group in the current study since they were taller and heavier than artistic gymnasts of similar age (João and Filho, 2015). Based on our results, the amount of training hours per week seems to be substantially lower for TeamGym athletes compared to other gymnastic disciplines (Edouard et al., 2018).

The large sex differences for most of the test results presented in this study help to explain the fundamental differences in specific performance characteristics related to sex differences in TeamGym performance. The Code of Points has identical difficulty values for all elements in the routines for females and males during competitions, which may be an obstacle for females due to the large differences in physical performance. In comparison, females and males compete in different apparatuses and routines in artistic gymnastics and the Code of Points differs according to that. The participants in the current study were chosen for the national TeamGym team with selection criteria according to the gymnastic performance level. The same criteria were used for juniors and seniors to select the team, which could be an obstacle for juniors that hit puberty late, especially for male juniors. Since our results indicate that physical growth varies between sexes, physical vs. technical abilities should probably be considered differently by coaches/trainers in the pubertal male vs. female TeamGym athlete's training (Lloyd and Oliver, 2012).

Limitations

In the current study, a cross-sectional study design was employed to provide descriptive information about the physical abilities of Swedish elite TeamGym athletes. Due to this, some findings should be interpreted with caution since such a design is inadequate for determining cause and effect relationships. For determining the effect of sex and age-group on the tested variables a prospective 5-year cohort study would have been more robust from a scientific perspective. However, such a study design was not possible to conduct on our target group of Swedish elite TeamGym athletes due to a multitude of factors. One main problem with such a design would have been related to the recruitment of athletes and potential drop-outs. Due to the cross-sectional study design, some results should be interpreted with caution, especially the interaction effects between sex and age-group. However, due to the sparse amount of published data on elite TeamGym athletes, the current study, based on a relatively big sample of elite athletes, provides important normative data for athletes, coaches, and trainers.

CONCLUSIONS AND PERSPECTIVES

Large sex differences were observed for most of the physical performance tests. Females had better flexibility than males, whereas males showed substantially better strength, jumping, speed, and endurance performance. The senior athletes performed better than the junior athletes in the pull-ups, dips, SJ, CMJ, CMJa, and 20-m linear sprint-run tests. However, the findings showed that there were small differences between junior and senior females with only significant differences observed for the strength tests. In contrast, between junior and senior males, significant differences were also revealed for jump, and sprint performances. These findings can be used for physical profiling by coaches when designing preparation strategies for athletic development for different age and sex groups. In addition, these results could be used for upcoming updates of the Code of Points ranking system for further development of the TeamGym discipline.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by The Swedish Ethical Review Board. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

SH and EA designed the study, interpreted the results, and wrote the first draft. SH collected data. EA performed the statistical analysis and the presentation of the results. Both authors revised the manuscript and approve the final version to be published and agree to be accountable for all aspects of the work.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2021.653503/full#supplementary-material

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Volume and Intensity of Locomotor Activity in International Men's Field Hockey Matches Over a 2-Year Period

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The locomotor demands of international men's field hockey matches were investigated across positions (DEF, MID, FWD) and playing quarters. Volume (i.e., total values) and intensity (i.e., relative to playing time) data were collected using 10-Hz GPS/100-Hz accelerometer units from the #11 world-ranked (WR) team, during 71 matches, against 24 opponents [WR 12 ± 11 (range, 1–60)]. Mean ± SD team total distance (TD) was 4,861 ± 871 m, with 25% (1,193 ± 329 m) "high-speed running" (>14.5 km h^{-1}) and 8% (402 ± 144 m) "sprinting" (>19.0 km h^{-1}). Reduced TD (range, −3 to 4%) and average speed (range, −3.4 to 4.7%) occurred through subsequent quarters, vs. Q1 ($p < 0.05$). A "large" negative relationship ($r = -0.64$) was found between playing duration and average speed. Positional differences ($p < 0.05$) were identified for all volume metrics including; playing duration (DEF, 45:50 ± 8:00 min; MID, 37:37 ± 7:12 min; FWD, 33:32 ± 6:22 min), TD (DEF, 5,223 ± 851 m; MID, 4,945 ± 827 m; FWD, 4,453 ± 741 m), sprinting distance (DEF, 315 ± 121 m; MID, 437 ± 144 m; FWD, 445 ± 129 m), and acceleration efforts (>2 m s^{-2}; DEF, 48 ± 12; MID, 51 ± 11; FWD, 50 ± 14). Intensity variables similarly revealed positional differences ($p < 0.05$) but with a different pattern between positions; average speed (DEF, 115 ± 10 m min^{-1}; MID, 132 ± 10 m min^{-1}; FWD, 134 ± 15 m min^{-1}), sprinting (DEF, 7 ± 3 m min^{-1}; MID, 12 ± 4 m min^{-1}; FWD, 14 ± 4 m min^{-1}), and accelerations (DEF, 1.1 ± 0.3 n min^{-1}; MID, 1.4 ± 0.2 n min^{-1}; FWD, 1.5 ± 0.3 n min^{-1}). Physical outputs reduced across playing quarters, despite unlimited substitutions, demonstrating the importance of optimizing physical preparation prior to international competition. Volume and intensity data highlight specific positional requirements, with forwards displaying shorter playing durations but greater high-intensity activities than defenders.

Keywords: acceleration, speed, team sports, GPS, hockey, accelerometer

INTRODUCTION

International hockey (sometimes referred to as "field hockey") tournaments are characterized by a high "density" of matches, with the Olympic Games requiring players to play eight matches within 16 days, to win a medal. Thus, a comprehensive understanding of the physical demands of the game is necessary, to prepare players appropriately. Over the past two decades, hockey has undergone multiple rule changes. This includes, unlimited substitutions (1992), "fast" restarts (2009), the addition of a sixth outfield substitute (2013) and in 2015, changing the match format from two 35–min halves, to four 15–min quarters (International Hockey Federation, 2019). Emerging evidence indicates these changes have altered the locomotor demands, with an increased proportion of high-intensity activities (Ihsan et al., 2018; Morencos et al., 2018); however, the reporting of the locomotor demands of men's hockey since 2013 and 2015 remains limited.

The physical demands of hockey may be monitored using wearable miniature electro-mechanical devices, providing both global positioning system (GPS) and inertial measurement unit (IMU) data (Cummins et al., 2013). These devices provide distances traveled at different velocities (Willmott et al., 2018) and can quantify specific movements such as accelerations, decelerations, or changes of direction (James et al., 2021). Since the 2013/2015 rule changes, it has been suggested that players cover a similar total distance (∼8,400 m) (Ihsan et al., 2018) within the modern game, compared with the historical 70-min format (∼8,000–8,500 m) (Lythe and Kilding, 2011; Buglione et al., 2013). However, these data represent extrapolated data to the respective full match durations (60/70 min) and due to the shortened modern match duration, the absolute total distance (TD) covered by players at the 2016 Olympic Games was considerably lower [∼5,600–6,500 m (McMahon and Kennnedy, 2019)]. Thus, whilst extrapolated data enables comparisons against other sports and/or hockey match formats, these data remain hypothetical and do not represent the actual activity experienced by players (Polglaze et al., 2018; Lombard et al., 2021). Nevertheless, there appears a greater proportion of high-speed running (>14/15 km h^{-1}) within the modern game (Lombard et al., 2017; Ihsan et al., 2018). Coaches also recognize an increased importance of such high-speed running for successful performance, by implementing tactical rolling substitutions or "rotation" strategies, to maintain high physical outputs (Linke and Lames, 2017). Therefore, training methods that complement this trend appear popular, with international teams implementing repeated-sprint training to improve this specific aspect of performance (Brocherie et al., 2015; James and Girard, 2020). Increased high-speed running during matches is theoretically concurrent with additional high-intensity accelerations and decelerations. The monitoring of these actions is pertinent, as they are associated with the development of neuro-muscular fatigue and muscle damage in other team-sports, such as soccer (de Hoyo et al., 2016). Recent data indicates hockey players undertake ∼100 "high-intensity" accelerations (Ihsan et al., 2018) and decelerations (Chesher et al., 2019) during international matches. During six World League matches, Ihsan et al. (2017) observed 1.2–1.5 accelerations and 1.3–1.7 decelerations per min^{-1}, using a comparable threshold of 2 m s^{-2}. However, the reporting of these movements in the modern game remains somewhat limited. Therefore, a comprehensive understanding of the locomotor demands of international hockey (i.e., running volume and intensity) at both a team and positional level is necessary, to facilitate effective training prescription, recovery strategies, and minimize injury risk (Bourdon et al., 2017).

Few studies have investigated both the volume and intensity of locomotor demands of international men's hockey since 2015. McMahon and Kennedy (2019) reported absolute (i.e., not extrapolated) TDs of 6,153 ± 990 m, 5,783 ± 810 m, and 5,451 ± 793 m for defenders (DEF), midfielders (MID), and forwards (FWD), respectively, across three tournaments (16 matches), which included the Olympic Games. The most high-speed distance (≥15 km h^{-1}) was covered by MID (1,446 ± 264 m), followed by FWD (1,359 ± 296 m), and DEF (1,123 ± 373 m). When interpreted relative to typical playing durations, these data allude to positional differences in the locomotor demands of modern hockey. However, playing intensity data (i.e., relative to playing time) such as average speed [meters per minute (m min^{-1})], or the frequency of specific movements such as the total accelerations and decelerations, were not reported. Ihsan et al. (2018) collected data from a similar number of matches ($n = 14$), played by the Singapore national team [2018 world ranking (WR) #35–40]. Based upon data extrapolated to the full-match duration, the authors identified FWD as the most demanding position, followed by MID and finally DEF. However, the absolute distances covered by players were not reported nor average speed data without extrapolation. Therefore, different interpretations of the demands experienced by FWDs may arise from the dichotomous reporting of either relative (Ihsan et al., 2018) or absolute data (McMahon and Kennnedy, 2019). Average speed data without extrapolation had earlier been reported by Ihsan et al. (2017) from six international matches, indicating the range of team whole-match average values to be between 121 and 133 m min^{-1}. However, the absolute volume (i.e., total values) and intensity (i.e., relative to time) of locomotor demands across different positions and the four quarters from a large number of matches, have yet to be reported in unison since the 2013 or 2015 rule changes. Consequently, relationships between total playing time and playing intensity, which may directly inform substitution strategies that seek to maintain physical outputs throughout matches, have yet to be identified. Moreover, reporting of the locomotor demands from a large sample of matches containing a variety of opponent and tournament standards is warranted. This reflects that the standard of competition elicits an independent effect on playing demands (Jennings et al., 2012a; McMahon and Kennnedy, 2019), which may bias data derived from smaller samples of matches.

Therefore, the aims of this study were to utilize data collected from a top-15 world-ranked team to; (i) comprehensively report GPS and IMU-derived volume and intensity of the locomotor demands across a large sample of international men's hockey matches, (ii) investigate differences in the whole-match locomotor demands between major positional groups (DEF, MID, FWD), (iii) investigate differences in the whole-team locomotor demands across playing quarters, and (iv) identify whether relationships existed between playing time and match intensity variables. We hypothesized that the locomotor demands would differ between positions, with FWD and MID completing more high-speed running, sprinting distance, and sprinting efforts, than DEF, yet locomotor outputs would reduce through the four quarters, and with increased playing time.

METHODS

Experimental Approach to the Problem

A retrospective analysis was undertaken of 71 international matches, played across a two-year period (March 2018–November 2019). There were 24 different opponents (WR, 12 ± 11; range, 1–60). Each player participated in an average of 40 ± 20 matches (range, 9–66). Data were only derived from official test matches and tournaments including; Hockey World Cup, Asian Games, Asian Champions Trophy, and World Series Finals. Practice matches were excluded. Data are reported in terms of both volume (i.e., total values) and intensity [i.e., relative to playing time (per min)].

Subjects

Twenty-seven male, international hockey players from the Malaysia national team (2018 WR #12, 2019 WR #11) participated in the study (nine DEF, seven MID, and 11 FWD; age 25 ± 4 years, stature 172 ± 5 cm, body mass 68 ± 6 kg, sum of seven skinfolds 45.3 ± 10.8 mm). Players typically undertook 10 training sessions per week, two strength training, and eight field sessions. Three field sessions contained a greater physical conditioning emphasis, one session was active recovery and the remaining four sessions a greater technical emphasis. The study had institutional ethical approval, and all analysis was conducted retrospectively on anonymous data, in accordance with the Declaration of Helsinki (2013).

Procedures

Data were collected using a triaxial 10 Hz GPS/100 Hz accelerometer unit (G5 firmware v. 7.40, Catapult Sports, Australia) harnessed between the scapulae in a customized sports vest, with which players were familiarized from daily training. Wherever possible, players used the same device and vest. Equipment failures resulted in five players receiving replacement devices during the 2 years. For one tournament (six matches), players used different devices from the same manufacturer (Catapult S5, firmware v. 7.32). Devices were turned on and placed in the center of the pitch for 10 min prior to use. Where this was not possible (Hockey World Cup and World Series Finals), devices were worn throughout the warm-up (∼40-min), which was followed by 4-min static, in the center of the pitch, for national anthems.

Data Processing

Devices were downloaded using a *Catapult Sports* docking station and processed using *Openfield* software (version 2.3.3, build #52841). Match data were processed live, by the same individual. This involved excluding data associated with large breaks in play; between playing quarters, substitutions, sin-bins, penalty corners, video referrals, major injuries, and goal scoring (Ihsan et al., 2018). Therefore, data used for analysis pertains to situations where the game clock is running and may be considered "ball-in-play time." The total playing time for each player was used to calculate their respective intensity data.

Running $>$14.5 km h^{-1} was classified as "high-speed running" and $>$19.0 km h^{-1} as "sprinting." Accelerations and decelerations are reported from GPS data (Catapult Gen2) and classified as either "high-intensity" (HI, 2.0–3.5 m s^{-2}) or "very high-intensity" (VHI, $>$3.5 m s^{-2}) events. Total accelerations or decelerations were taken as the sum of HI and VHI events (i.e., all events $>$2 m s^{-2}) as per current hockey literature (White and MacFarlane, 2015; Ihsan et al., 2018). Velocity and acceleration dwell times were 1.0 and 0.4 s, respectively.

Data from the IMU were used to calculate *Playerload* (Gómez-Carmona et al., 2020). Specific movements that were identified by the IMU (accelerations, decelerations, and left/right changes of direction) were similarly categorized as VHI if they exceeded 3.5 m s^{-2}, and subsequently combined into a single metric of multi-directional load (total VHI movements) (James et al., 2021). This metric therefore encompassed all movements in the horizontal plane and was processed using inertial movement analysis (version 2) (Catapult Sports, 2019).

Measures of GPS quality, horizontal dilution of precision (HDOP, 0.75 ± 0.14) and satellite number (11.6 ± 0.8) (Malone et al., 2017) were considered excellent by the manufacturer guidelines. We discarded data not meeting the following inclusion criteria; minimum of nine outfield players (0 cases), no data recorded or values visually identified as a technological error (two cases), and minimum of seven satellites during match (one case). These inclusion criteria resulted in the removal of one player's GPS data for one match and two further player's IMU data for two different matches, resulting in a total of three match files being removed, leaving 1,106 whole-match files for analysis. Where errors were detected, the corresponding GPS or IMU data was retained if this was considered accurate (verified by three authors, independently). We did not apply a minimum playing time threshold because only nine playing-quarter records had a duration of $<$3 min per quarter (out of a total of 4,399 individual playing-quarter records), which was the minimum planned on-pitch "rotation" for any match across the 2-year period.

Statistical Analyses

Data are presented as mean ± SD and were analyzed using SPSS (v.26, IBM, USA) with statistical significance as $p < 0.05$. All outcome variables were assessed for normality of distribution using histograms, boxplots, and measures of skewness and kurtosis, before analysis. Descriptive statistics, including the coefficient of variation (CV; [SD/mean]*100) and smallest worthwhile change (SWC; 0.2*SD) were calculated from whole-match averages (Hopkins, 2014). One-way ANOVA compared the whole-match volume and intensity data of DEF, MID, and FWD, with Bonferroni *post-hoc*. Where homogeneity of variance was not achieved, Welch's corrected F value was used to indicate statistical significance. Factorial repeated measures ANOVA were used to identify interaction effects (playing quarter * position), with Bonferroni *post-hoc*. Relationships between playing time and playing intensity were analyzed using Pearson product–moment correlations.

RESULTS

Whole-Match Descriptive Data and Positional Differences

Descriptive reporting of whole-match volume and intensity data is displayed in **Table 1**. **Figure 1** displays the distribution of volume data for all playing quarters, relative to playing position, of all players. Differences between positions in whole-match averages were observed for all variables ($p < 0.05$). Similarly, **Figure 2** displays intensity data for all playing quarters, by playing position, and revealed positional differences within all variables ($p < 0.05$). For clarity, *post-hoc* comparisons between positions and effect sizes are provided in **Table 2**.

Between Playing Quarters

Analysis of volume data revealed statistical differences between quarters for TD, high-speed running, sprinting distance, sprinting efforts, *Playerload*, accelerations, decelerations, and VHI movements (all $p < 0.05$). *Post-hoc* analysis is displayed in **Figure 3**. Similarly, analysis of intensity data revealed differences between playing quarters for average speed, high-speed running per minute, sprinting efforts per minute, *Playerload* per minute, acceleration efforts per minute, deceleration efforts per minute, and VHI movements per minute (all $p < 0.05$, **Figure 3**). There was no difference between quarters for playing duration or sprinting distance per minute ($p > 0.05$).

Relationships Between Playing Duration and Match Intensity

The strongest relationship (±95% confidence interval) with playing duration was observed for average speed ($r = -0.64$ [±0.04], **Figure 4**). There were also relationships (all $p < 0.001$) with high-speed running per minute ($r = -0.61$ [±0.04]), *Playerload* per min ($r = -0.61$ [±0.04]), sprinting ($r = -0.55$ [±0.04]), sprinting efforts ($r = -0.53$ [±0.04]), acceleration efforts per minute ($r = -0.51$ [±0.04]), and deceleration efforts per minute ($r = -0.49$ [±0.04]).

DISCUSSION

This study utilized data from a top-15 world-ranked team to comprehensively report the volume and intensity of locomotor demands in international men's hockey matches by playing position and quarters. Our findings, from 1,106 individual player records and 71 matches, indicate the first playing quarter (Q1) has the highest demands. We observed reductions in both TD (range, 3–4%) and average speed (range, 3.4–4.7%) through subsequent quarters, compared with Q1. Players performed 50 ± 12 accelerations and 60 ± 14 decelerations per game, equivalent to performing a high-intensity movement once or twice per minute (**Table 1**). Differences in playing durations and demands between positions existed, with DEF spending more time on the pitch (+18% vs. MID, +27% vs. FWD) accruing larger total distances (+5% vs. MID, +15% vs. FWD), but generally playing at a lower intensity than MID and FWD (m min^{-1}; −15% vs. MID, −17% vs. FWD). Finally, we observed strong negative relationships between total playing time and intensity metrics, reinforcing the need for effective physical training and recovery practices, as well as structured substitution policies, to maintain physical outputs throughout a match.

Whole-Match Demands

At the team level, players covered 4,861 ± 871 m per game, with 25% (1,193 ± 329 m) considered high-speed running (>14.5 km h^{-1}) and 8% (402 ± 144 m) sprinting (>19.0 km h^{-1}). These total and high-speed distances are comparable with the limited data pertaining to international men's hockey since the 2013 and 2015 rule changes (Ihsan et al., 2017; McMahon and Kennnedy, 2019). However, the TD that we report is considerably lower than previous extrapolated data (FWD, 8,922 ± 818 m; MID, 8,613 ± 406 m; DEF, 7,631 ± 753 m) (Ihsan et al., 2018), despite the same game format and apparent similarity of data processing (i.e., removal of time-outs and penalty corners). This supports previous suggestions that extrapolation does not effectively characterize the true demands experienced by players (Polglaze et al., 2018; Lombard et al., 2021). Our data represent the absolute mean and range of values that may occur during international matches. As we did not apply inclusion criteria based upon a minimum playing time, the larger values within the ranges we report are highly pertinent for training benchmarks. These data may be considered "worst-case scenarios" when players experience additional demands, for example, when a teammate is injured or sent to the sin-bin (**Table 1**).

The observations that 28% and 8% of TD involves running >14.5 and >19.0 km h^{-1}, respectively, reaffirm pre-2015 observations that hockey remains an intermittent high-intensity sport, whereby periods of low-intensity running are interspersed with high-intensity efforts (Lythe and Kilding, 2011). The sprinting distance (8%) exceeds the 6% previously reported from the New Zealand men's team in 2011 (Lythe and Kilding, 2011). While modest, this supports a trend towardz a greater proportion of high-speed running and sprinting in the modern game (Ihsan et al., 2018; McGuinness et al., 2019b; McMahon and Kennedy, 2019). Furthermore, the team's average speed (127 ± 15 m min^{-1}), exceeds historical data from other international teams, e.g., 116 m min^{-1} (no SD reported) (New Zealand, 2011 WR #7) (Lythe and Kilding, 2011) and 124 m min^{-1} (95% CI, 120–128) (Scotland, 2015 WR #26) (White and MacFarlane, 2015). It is comparable with that of 12 players from the Singapore national team in 2015 (121–133 m min^{-1}) (Ihsan et al., 2017). Nevertheless, the team average speed data are below that of the then world number 1 Australia team, during the two-half match format (131 ± 11 m min^{-1}) (Polglaze et al., 2015), which may reflect a difference in physical outputs of the higher ranked sides vs. the current team (Gabbett, 2013).

The current data support previous suggestions that the standard of competition may influence playing demands (McMahon and Kennnedy, 2019), with the team's average speed

TABLE 1 | Descriptive data for volume and intensity of whole match locomotor demands in international men's hockey.

	Mean ± SD	CV%	Median	Range	IQR	SWC
Volume						
Playing duration (min)	38:47 ± 08:49	23%	38:35	07:28–61:32	32:21–44:55	01:46
Total distance (m)	4,861 ± 867	18%	4,898	950–7,250	4,270–5,484	173
High-speed running (m)	1,191 ± 328	28%	1,190	228–2,331	970–1,399	66
Sprinting (m)	401 ± 144	36%	395	51–962	293–494	29
Sprinting efforts	21 ± 7	33%	21	2–49	16–26	1
Playerload (a.u.)	469 ± 84	18%	472	98–760	418–527	17
Acceleration efforts	50 ± 12	25%	49	11–98	42–57	2
Deceleration efforts	60 ± 14	24%	59	13–110	50–69	3
VHI movements	17 ± 8	44%	17	0–47	13–22	2
Intensity						
Average speed (m min^{-1})	127 ± 15	12%	128	73–170	117–137	3
High-speed running (m min^{-1})	32 ± 11	33%	32	9–68	25–39	2
Sprinting (m min^{-1})	11 ± 5	41%	11	2–27	8–14	1
Sprinting efforts (n min^{-1})	0.6 ± 0.2	37%	0.6	0.1–1.3	0.4–0.7	0.04
Playerload with (a.u. min^{-1})	12.4 ± 1.9	15%	12.2	7.4–19.1	11.1–13.3	0.4
Acceleration efforts (n min^{-1})	1.3 ± 0.3	26%	1.3	0.4–2.6	1.1–1.5	0.1
Deceleration efforts (n min^{-1})	1.6 ± 0.4	25%	1.5	0.7–3.3	1.3–1.8	0.1
VHI movements (n min^{-1})	0.5 ± 0.2	41%	0.4	0.0–1.1	0.3–0.6	0.04

*Data represent 1,106 individual player match-records, derived from 71 international matches. Acceleration and deceleration efforts identified using GPS data, when >2 m s^{-2}. VHI movements is the sum of all movements in the horizontal plane (i.e., accelerations, decelerations, and left/right changes of direction), identified from the inertial sensor, that exceeded 3.5 m s^{-2}. CV, coefficient of variation (CV; [SD/mean]*100); IQR, interquartile range; SWC, smallest worthwhile change.*

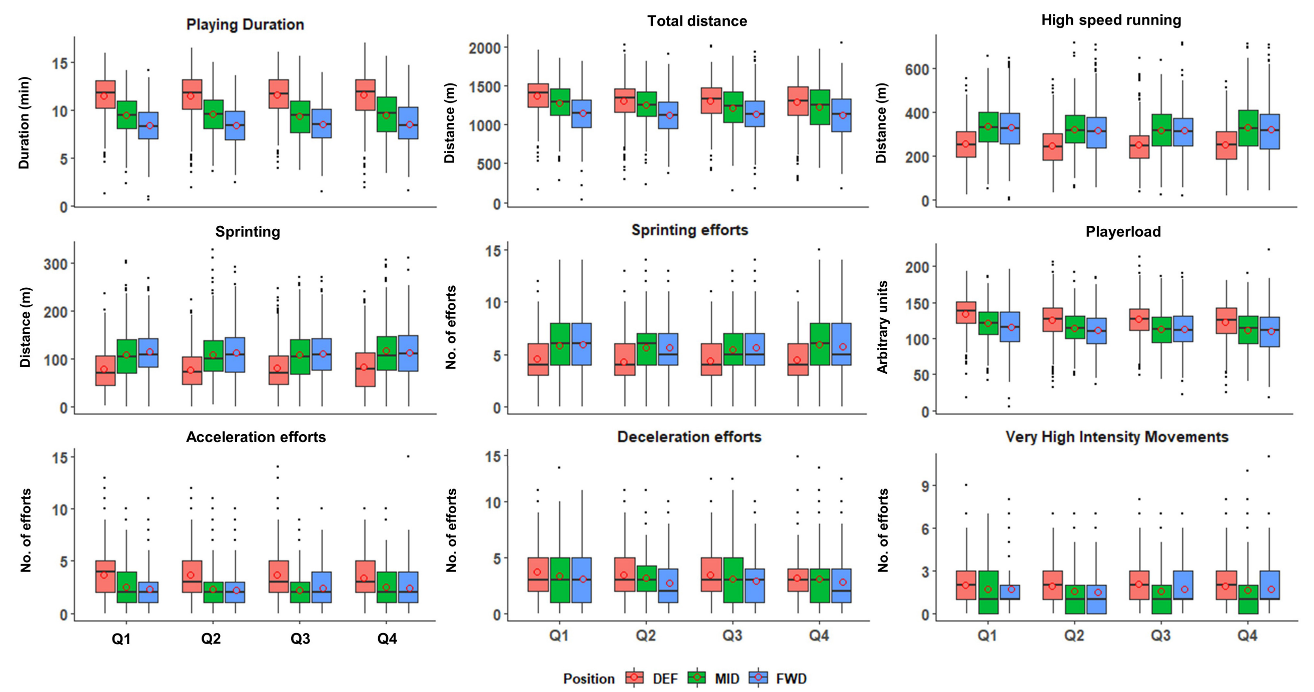

FIGURE 1 | Volume of locomotor demands in international hockey across the four playing quarters and presented by playing positions. Data represent 4,399 individual playing-quarter match-records, derived from 71 international matches. DEF, defenders; MID, midfielders; FWD, forwards; Q1, first quarter; Q2, second quarter; Q3, third quarter; Q4, fourth quarter. Box edges represent 25 and 75% of the interquartile range (IQR). Horizontal lines within the box, median; circles within the box, mean; solid dots, outliers (>1.5 IQR); whiskers represent ±1.5 times *IQR. A.U., arbitrary units.

TABLE 2 | Whole-match positional data and Cohen's *d* effect sizes (ES; ±95% confidence interval) from 71 international matches.

	Defenders	Midfielders	Forwards	DEF vs. MID	DEF vs. FWD	MID vs. FWD
				ES (95% CI)	ES (95% CI)	ES (95% CI)
Volume						
Playing duration (min)	45:45 ± 08:05	37:37 ± 07:12*	33:32 ± 06:22*#	1.07 (0.91, 1.22)	1.69 (1.52, 1.86)	0.60 (0.46, 0.75)
Total distance (m)	5,223 ± 851	4,945 ± 827*	4,453 ± 741*#	0.33 (0.19, 0.48)	0.97 (0.82, 1.12)	0.63 (0.48, 0.78)
High-speed running (m)	998 ± 289	1,299 ± 298*	1,266 ± 310*	1.02 (0.87, 1.18)	0.89 (0.74, 1.04)	0.11 (−0.04, 0.25)
Sprinting (m)	315 ± 121	437 ± 144*	445 ± 129*	0.91 (0.76, 1.06)	1.03 (0.88, 1.19)	0.06 (−0.09, 0.20)
Sprinting efforts	18 ± 6	23 ± 7*	23 ± 7*	0.79 (0.64, 0.94)	0.82 (0.67, 0.97)	0.01 (−0.13, 0.15)
Playerload (a.u.)	507 ± 81	459 ± 76*	445 ± 83*#	0.60 (0.45, 0.75)	0.75 (0.60, 0.90)	0.19 (0.04, 0.33)
Acceleration efforts	48 ± 12	51 ± 11*	50 ± 14	0.22 (0.07, 0.36)	0.12 (−0.02, 0.26)	0.08 (−0.07, 0.22)
Deceleration efforts	61 ± 14	63 ± 15*	55 ± 13*#	0.20 (0.06, 0.35)	0.42 (0.27, 0.56)	0.61 (0.46, 0.76)
VHI movements	20 ± 8	16 ± 7*	16 ± 7*	0.56 (0.41, 0.71)	0.60 (0.46, 0.75)	0.04 (−0.11, 0.18)
Intensity						
Average speed (m min^{-1})	115 ± 10	132 ± 10*	134 ± 15*	1.73 (1.57, 1.9)	1.50 (1.34, 1.66)	0.14 (0, 0.29)
High-speed running (m min^{-1})	22 ± 7	35 ± 8*	39 ± 10*#	1.78 (1.61, 1.95)	1.93 (1.76, 2.11)	0.40 (0.25, 0.54)
Sprinting (m min^{-1})	7 ± 3	12 ± 4*	14 ± 4*#	1.41 (1.25, 1.57)	1.84 (1.67, 2.01)	0.44 (0.29, 0.59)
Sprinting efforts (n min^{-1})	0.4 ± 0.1	0.6 ± 0.2*	0.7 ± 0.2*#	1.39 (1.23, 1.55)	1.72 (1.55, 1.89)	0.44 (0.29, 0.59)
Playerload per min (a.u. min^{-1})	11.2 ± 1.3	12.4 ± 1.3*	13.4 ± 2.1*#	0.86 (0.71, 1.01)	1.26 (1.10, 1.42)	0.61 (0.46, 0.76)
Acceleration efforts (n min^{-1})	1.1 ± 0.3	1.4 ± 0.2*	1.5 ± 0.3*#	1.09 (0.93, 1.24)	1.32 (1.16, 1.48)	0.45 (0.31, 0.60)
Deceleration efforts (n min^{-1})	1.3 ± 0.3	1.7 ± 0.3*	1.7 ± 0.4*	1.15 (0.99, 1.30)	0.93 (0.78, 1.08)	0.09 (−0.06, 0.23)
VHI movements (n min^{-1})	0.5 ± 0.2	0.4 ± 0.2	0.5 ± 0.2#	0.13 (−0.01, 0.27)	0.14 (0, 0.29)	0.26 (0.11, 0.4)

*Different from defenders.

#Different from midfielders (forwards only).

DEF, defenders; MID, midfielders; FWD, forwards. Acceleration and deceleration efforts identified using GPS data, when >2 m s^{-2}. VHI movements is the sum of all movements in the horizontal plane (i.e., accelerations, decelerations, and left/right changes of direction), identified from the inertial sensor, that exceeded 3.5 m s^{-2}.

higher than the Spanish domestic league (105–123 m min^{-1}) (Romero-Moraleda et al., 2020). However, intensity data must be interpreted with caution, as a falsely high playing intensity may be derived if only time "in-play" data are analyzed, as this negates rest periods associated with events such as; goal scoring, substitutions, or between quarters/half-time (White and MacFarlane, 2013). Therefore, our "ball-in-play" data may represent a higher intensity than players experienced during the match. However, it should be noted that failing to remove data associated with breaks in-play, may misrepresent the typical intensities experienced when the ball is in play. Finally, our approach enables comparisons to be made between matches and across sports, indicating hockey players maintain higher average speeds than in other team sports such as soccer, rugby union, and rugby league, but lower than Australian rules football (Aughey, 2011; Cummins et al., 2013).

Positional Differences

Our data reveal FWD to play for the shortest duration (33 ± 6 min), accumulating lower TD than both MID (37 ± 7 min) and DEF (45 ± 8 min) but display higher intensities (**Figure 1**). These differences in playing durations are consistent with observations from men's (Jennings et al., 2012b) and women's international hockey pre-2015 (McGuinness et al., 2019b), as well as post-2015 women's hockey (McGuinness et al., 2019a). While the SD of playing time for DEF (±8 min) is larger than MID (±7 min) and FWD (±6 min), all positions are comparable when expressed as a CV (i.e., relative to average playing time; 18–19%; **Table 1**). This indicates similar variability of playing time across positions, despite the team's planned rotation strategy sometimes involving fewer DEF substitutions and thus potential for longer playing times during situations such as sin-bins or injuries.

Our findings that FWD achieved the lowest (absolute) TD and *Playerload* somewhat contrasts with previous conclusions from extrapolated data, that FWD have the highest "running demands" (Ihsan et al., 2018). This reinforces the importance of reporting and interpreting both the constituent parts of locomotor demands, i.e., the volume and intensity of work completed by players, for effective load management. The lower average speed of DEF has previously been linked to a higher playing duration (Polglaze et al., 2015). Indeed, we identified a strong negative relationship between total playing time and average speed ($r^2 = 0.41$, **Figure 4**) across the 71 matches. This relationship may be considered "large" (Hopkins et al., 2009) and highlights the importance of a structured substitution policy, to balance playing time across the team and facilitate higher intensities across playing quarters (Linke and Lames, 2017).

We observed differences in the volume of high-intensity activities between positions, with DEF completing less high-speed running, sprinting meters, and sprinting efforts, than both MID and FWD, who did not differ (**Figure 1**). McMahon and Kennnedy (2019) reported comparable high-speed running demands (classified as ≥15 km h^{-1}), with this representing ∼18% of TD for DEF, ∼25% for MID, and ∼25% for FWD.

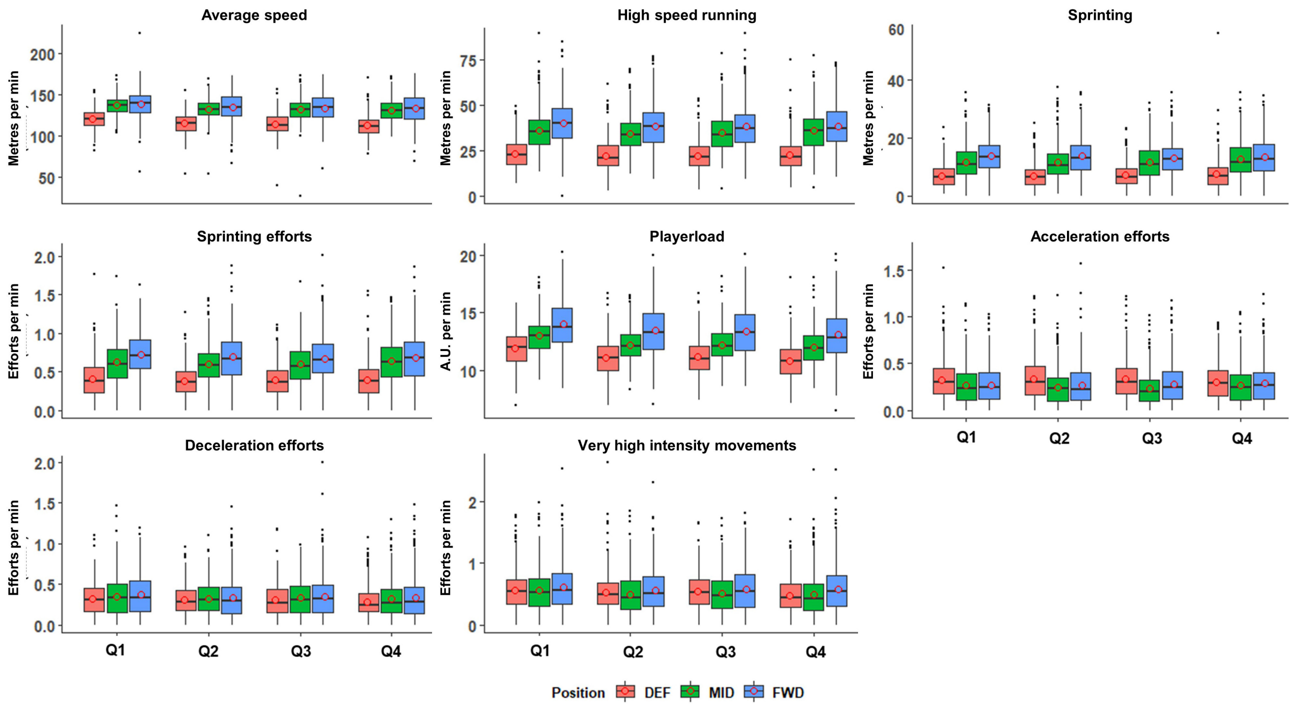

FIGURE 2 | Intensity of locomotor demands in international hockey across the four playing quarters and presented by playing positions. Data represent 4,399 individual playing-quarter match records, derived from 71 international matches. DEF, defenders; MID, midfielders; FWD, forwards; Q1, first quarter; Q2, second quarter; Q3, third quarter; Q4, fourth quarter. Box edges represent 25 and 75% of the interquartile range (IQR). Horizontal lines within the box, median; circles within the box, mean; solid dots, outliers (>1.5 IQR); whiskers represent ±1.5 times *IQR. A.U., arbitrary units.

This compares with our high-speed running (≥14.5 km h^{-1}) percentages of 19% (DEF), 26% (MID), and 28% (FWD). However, when expressed by playing time, FWD completed more of these high-intensity activities than MID, who in-turn completed more than DEF (**Figure 2**). While a similar pattern was found for accelerations per minute (FWD, 1.5 ± 0.3; MID, 1.4 ± 0.2; DEF, 1.1 ± 0.3, **Figure 2**), the total VHI movements detected by the IMU did not reveal the same pattern, with DEF completing more VHI movements than MID (**Figures 1**, **2**). This indicates a position-specific demand on DEF, independent of high-speed or locomotor running distances, as has been reported in soccer DEF (Dalen et al., 2016). In hockey, these demands likely include DEF performing shorter movements and/or changes of direction to eliminate an opponent's available space, making tackles or intercepting passes, thereby accruing more VHI movements.

Comparisons Between Playing Quarters

We observed reductions in the TD (range, 2.9–4.0%) during Q2, Q3, and Q4, compared with Q1 (**Figure 3**). Similarly, average speed reduced across playing quarters, compared with Q1 (range, 3.4–4.7%), with the lowest values during Q4. Reduced running outputs have been observed in men's hockey within both older (Lythe and Kilding, 2011; Jennings et al., 2012a) and modern match formats (Ihsan et al., 2018; Morencos et al., 2018). Interestingly, this is despite unlimited available substitutions. Unlike TD, high-speed metrics such as high-speed running distance, sprinting distance, and sprinting efforts revealed "U-shaped" responses (**Figure 3**), with the highest values observed during Q1 and Q4. This alludes to situational factors, such as score-line or tactical strategy, influencing high-speed running demands, in the absence of a linear reduction, which would be consistent with physiological fatigue. Indeed, the nature of the reduction in running outputs is not well-understood. We found the number of high-speed events per minute did not change across playing quarters. This indicates the higher volumes during Q1 and Q4 are interspersed with longer periods of lower intensity running, which is supported by the consistent decline in average speed. Ihsan et al. (2018) suggested players may pace throughout a game by altering low-intensity movements, thereby preserving higher speed running efforts. In contrast, Morencos et al. (2018) found Spanish domestic league players cover similar TD, but less high-speed distance and fewer sprinting efforts as the game progressed. Therefore, the pattern of running outputs across matches appears to vary between teams, likely due to factors including physical conditioning, team ranking, opponent ranking, and tactical strategy. Future research is therefore warranted into the effect of situational factors such as score-line and environmental conditions on these locomotor demands across a match.

Limitations

Our conclusions are drawn from only one team and may be susceptible to bias from the playing style and physiological

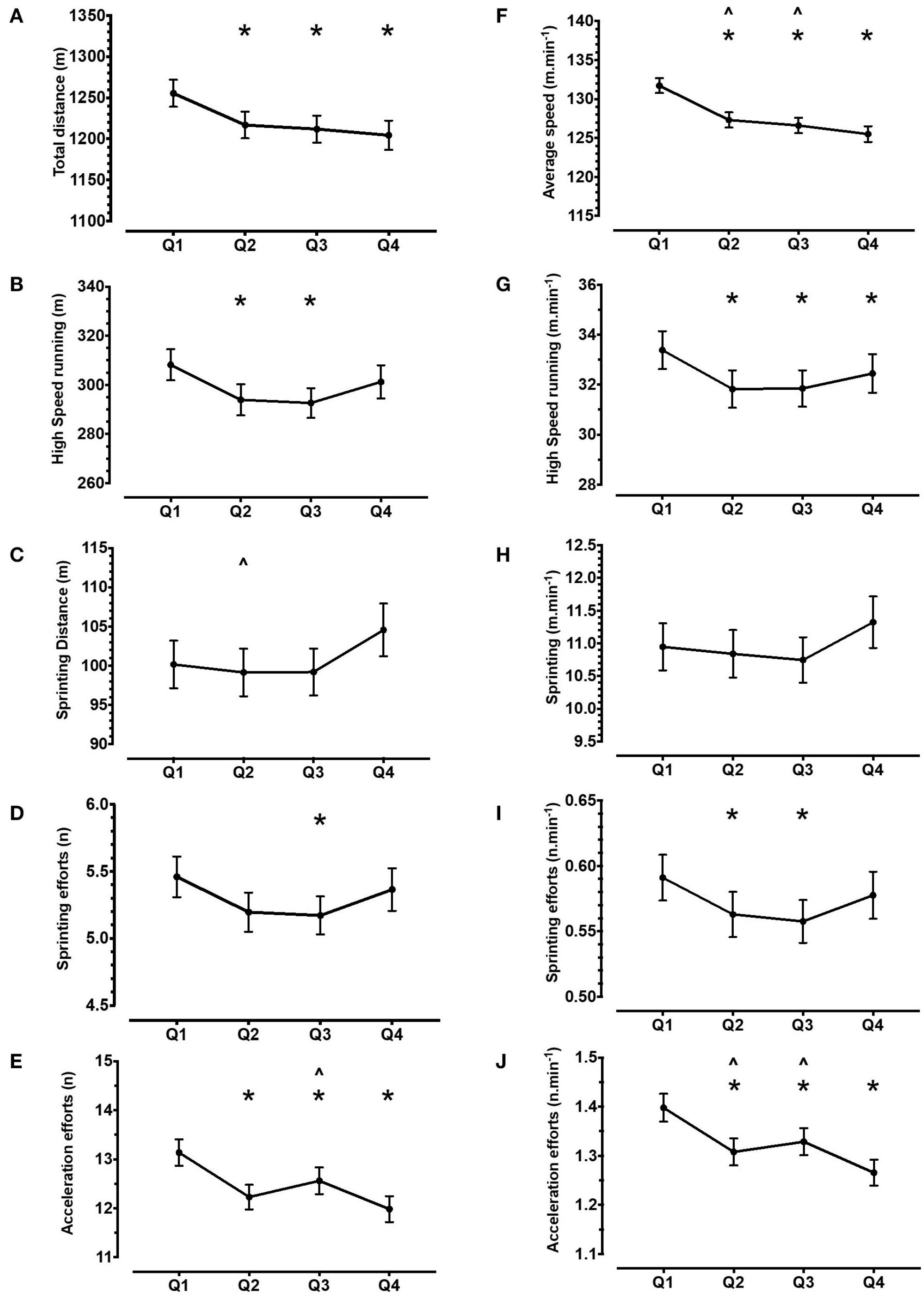

FIGURE 3 | Team average of the volume (left panel, plots **A–E**) and intensity (right panel, plots **F–J**) of locomotor demands across playing quarters. Error bars represent 95% confidence interval. Data represent 4,399 individual playing-quarter match records, derived from 71 international matches. Asterisk represents difference vs. Q1, Circumflex accent symbol represents difference vs. Q4 ($p < 0.05$).

characteristics of these players. Nevertheless, the inclusion of many opponents, standards of tournaments, and locations within our dataset somewhat mitigates these potential sources of bias. Moreover, the team had two different coaches within this period, who implemented different tactical approaches. Teams who implement different substitution strategies (i.e., not one DEF, two MID, and three FWD replacements) may observe different demands between positions or, less equitable playing time between individual players. Our investigation is focused upon whole-match or playing-quarter averages. Thus,

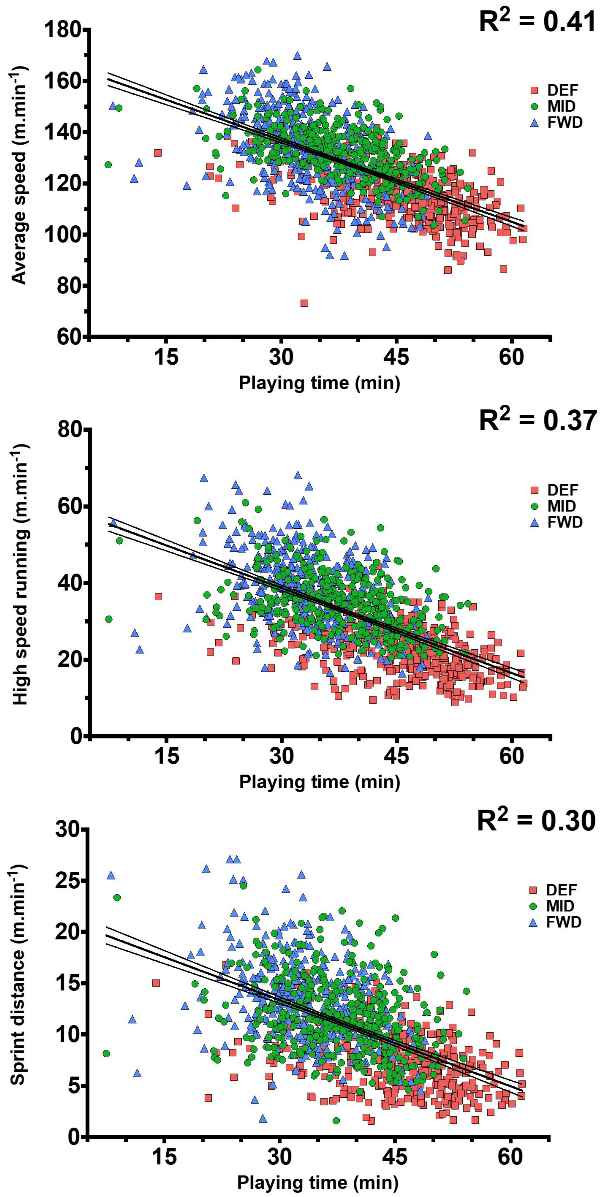

FIGURE 4 | Relationships between playing time and average speed **(Top)**, high-speed running per minute **(Middle)**, and sprinting distance per minute **(Bottom)**. Data derived from 71 international men's hockey matches (n = 1,106 samples). Dashed lines represent 95% confidence interval around trendline.

periods of higher intensity activity may be observed within playing quarters. Future analysis should therefore consider within-playing-quarter activity patterns by analyzing player rotation durations (McGuinness et al., 2021) and/or peak passages of play (Delves et al., 2019; McGuinness et al., 2020). Finally, our categorization into three positions neglects discrete differences within positions, such as the role of wing-backs or holding midfielders. However, as players often play multiple positions as part of the rotation policy, this confounds further positional differentiation.

PRACTICAL APPLICATIONS

These data demonstrate the need for practitioners and coaches managing player's physical loads to consider both the playing volume and intensity, in order to understand the true physical demands players experience during matches. These data can be used to design training programs containing suitable running volumes to prepare players for tournaments with a high match "density," e.g., up to eight match distances (∼4,818 m) across an Olympic 13-day tournament (∼38,000 m). The additional high-speed running completed by MID and FWD, compared with DEF, would exceed what may be considered the SWC in high-speed running for the whole team (66 m). Furthermore, when players repeat these loads eight times in 13 days, the accumulated difference would exceed the average of one game for all positions (**Table 1**). Therefore, position-specific conditioning would appear relevant when preparing for tournaments with multiple matches, such as the Olympics. Match intensity that is derived from whole-match averages, may provide training benchmarks, but risks under preparing players for the intensity experienced during individual quarters or shorter, intense passages of play (Delves et al., 2019; McGuinness et al., 2020). Thus, consideration should be given to identifying and replicating demanding passages of play within training, for suitable match preparation. As Q1 appears the most demanding quarter, there appears a need for optimizing pre-match priming strategies, nutrition, and warm-ups (McGowan et al., 2015). Furthermore, as some metrics display a U-shaped response, within-match strategies are also important. Finally, for effective player preparation, we highlight that replicating external match intensities we report, may not be optimal for stimulating specific, desirable physiological adaptations (Impellizzeri et al., 2019). Accordingly, the complimentary monitoring of internal training load is recommended, to understand the physiological stimulus that seeks to meet the demands of competition we describe.

DATA AVAILABILITY STATEMENT

The data analyzed in this study was subject to the following licenses/restrictions: direct any queries to the lead author. Requests to access these datasets should be directed to Carl A. James, carlalexanderjames@gmail.com.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Institut Sukan Negara. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CJ, OG, CS, AD, and AW conceived and designed the study, analyzed and interpreted the data, drafted and revised the manuscript, and approved the final version of the manuscript. CJ collected the data. All authors contributed to the article and approved the submitted version.

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ORIGINAL RESEARCH
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Talent Identification in an English Premiership Rugby Union Academy: Multidisciplinary Characteristics of Selected and Non-selected Male Under-15 Players

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Entry into an academy can be a defining moment for a promising young player. The aim of this study was to explore the multidimensional characteristics that differentiated selected and non-selected male under-15 rugby union players at an English Premiership academy. Seventy-four players (mean age 14.6 ± 0.3 years: selected $n = 29$; non-selected $n = 45$) were measured across nine characteristics from four overarching factors: (a) anthropometric ($n = 2$), (b) physiological ($n = 5$), (c) cognitive ($n = 1$), and (d) birth quartile. An ANOVA compared differences between groups (selected vs. non-selected), whilst a Welch's t-test and Cohen's d were used for further comparisons. A multivariate logistic regression was also used to predict selection. Results showed significant differences between selected and non-selected players for anthropometric ($P = 0.021$) and physiological factors ($P < 0.001$). Moreover, relatively older players were overrepresented with 65% born in the first half of the year, whereas no significant differences were apparent for the cognitive test. More specifically, selected players possessed greater body mass ($P = 0.022$, $d = 0.5$) and handgrip strength ($P = 0.020$, $d = 0.5$) compared to non-selected players, whilst multivariate analysis showed the 20 m sprint explained 25.4% of the variance ($P = 0.001$). Overall, it appears selection into an English Premiership rugby union academy may be due to enhanced physical attributes rather than cognitive abilities.

Keywords: talent development, Rugby Football Union, expertise, talent identification, selection, athlete development, LtAD

INTRODUCTION

Achieving professional status in sport is the quest of many young athletes across the globe (Till and Baker, 2020). Indeed, one of the increasing pressures for sport organizations is to identify promising young athletes and provide them with an optimal learning environment to facilitate long-term performance (Baker et al., 2013). The male rugby union (RU) talent pathway in England is comprised of an academy programme, delivered via 14 Regional Academies (currently aligned with 12 Premiership clubs, one Championship club, and one unaffiliated; Kelly et al., 2021b). Individuals are typically identified from age-grade or school rugby union, whereby they are selected at the end of the Under (U) 15 age group into Regional Academies (Till et al., 2020). Once selected into a Regional Academy at U15, the pathway consists of U18 and senior academy (e.g., U21) rosters to facilitate development toward the first team. Thus, it is plausible to suggest that initial selection into a RU academy at U15 can be a crucial moment for an aspiring young player.

Talent identification (TID) can be defined as recognizing young athletes with the potential to achieve expertise in a particular sport (Williams and Reilly, 2000). The TID process in RU is often influenced by a number characteristics, such as: (a) *anthropometric* (e.g., greater body size and mass; Fontana et al., 2015), (b) *physiological* (e.g., superior speed, strength, and power; Owen et al., 2020), (c) *cognitive* (e.g., advanced tactical skills; Sherwood et al., 2019), and (d) *birth quartile* (e.g., relatively older players overrepresented; Kelly et al., 2021a). From an anthropometric perspective, body mass and body fat percentage has been found to predict competition levels in youth RU players (Till et al., 2020; Dimundo et al., 2021). In a cross-sectional study on Italian players, Fontana et al. (2015) found that the lower the level of the player, the higher the percentage of fat mass was. Moreover, physiological attributes, such as sprint speed, strength, and power are regarded as important factors that differentiate between players based on age group, competition level, and position (Owen et al., 2020; Dimundo et al., 2021). For instance, Darrall-Jones et al. (2015) found that countermovement jump (CMJ) height, peak power, sprint momentum, acceleration speed, and isometric strength improved with age (i.e., U16–U21) in an English Premiership Regional Academy.

Cognitive characteristics, such as anticipation and decision-making skills (i.e., perceptual-cognitive expertise; see Mann et al., 2007 for a review), are also crucial for differentiating players based on ability levels, which has been explored in different rugby contexts including Australia, England, France, New Zealand and South Africa (Dimundo et al., 2021). As an example, Farrow et al. (2010) used video simulations to examine anticipatory skills, revealing that pattern recall could differentiate expert, intermediate, and novice Australian RU players. In addition, birth quartile appears to play an important role during initial selection into RU talent development pathways (Kelly et al., 2021a). Specifically, Kelly et al. (2021b) demonstrated that 42.5% of players selected into English Regional Academies at U15 across the last three seasons (2016–2019) were born in the first 3 months of the annual selection year (i.e., September, October, and November) compared to just 9.6% born in the last 3 months (i.e., June, July, and August). These phenomenon are commonly termed as relative age effects (RAEs; Cobley et al., 2009). Overall, since there are various factors that can influence selection into RU talent development pathways, it is important to consider a multidisciplinary research methodology whilst examining the TID process.

The initial selection into a RU academy at U15 is a critical time for all English Premiership clubs, since these players will form the core of the subsequent age groups for the proceeding years toward their respective first team. As part of forming the U16 age group, it is common practice for Regional Academies to hold an annual trial (or performance camp) for promising U15 players from their regional junior centers and developing player programme (Till et al., 2020). However, the multidisciplinary factors (i.e., anthropometric, physiological, cognitive, and birth quartile) that differentiate those who are selected, compared to those who are non-selected, are yet to be empirically evaluated. As such, the aim of this study was to explore the anthropometric, physiological, cognitive, and birth quartile characteristics that differentiated selected and non-selected U15 English Premiership RU academy players, as well as examine the factors that predicted selection. Moreover, a secondary aim of this study was to distinguish differences between selected and non-selected players based on position (i.e., forwards vs. backs).

METHODS

Participants

Seventy-four participants (mean age 14.6 ± 0.3 years: selected $n = 29$; non-selected $n = 45$) from an English Premiership RU Regional Academy participated in this study. Participants were also divided by their preferred playing position (selected forwards $n = 14$; non-selected forwards $n = 18$; selected backs $n = 15$; non-selected backs $n = 27$) for further analysis. Ethical approval was granted by Birmingham City University via the Health, Education, and Life Sciences Research Ethics Committee.

Procedures

The participants were invited to a four-day performance summer camp (i.e., annual trial) in an attempt to be selected for the U15 squad at an English Premiership RU Regional Academy. These participants are typically identified from community or school rugby, whereby the annual trial for the Regional Academy is delivered on an invitation-only basis (Till et al., 2020). Participants were pre-identified from existing Alongside specific RU training, participants were tested to record key performance parameters, which comprised of nine characteristics from the four overarching factors: (a) *anthropometric* (i.e., body height and mass), (b) *physiological* (i.e., 10 and 20 m sprint time, CMJ, isometric hip extension [IHE], and dominant handgrip strength), (c) *cognitive* (i.e., perceptual-cognitive video simulation test), and (d) *birth quartile* (i.e., date of birth). All physiological measures were collected following the same tests order, with a minimum of 3 min between tests, during day-1 of the performance camp. This approach allowed comparison between those who were subsequently selected and non-selected.

Participants' body height and mass were measured to the nearest 0.1 cm and 0.1 kg using a Seca Alpha stadiometer and calibrated Seca Alpha (model 220) scales wearing only shorts (e.g., Darrall-Jones et al., 2015). A standardized warm-up and two familiarization trials were performed before each physiological test. Sprint time over 10 and 20 m was recorded using timing gates (Brower Timing Systems, IR Emit. Draper, UT, USA). Each sprint started 30 cm behind the initial timing gate, with participants instructed to commence at a freely-chosen time and run maximally through the final 20 m timing gate (e.g., Darrall-Jones et al., 2015). A CMJ was performed with the participants hands placed on the hips while stood between two portable infrared recorders (Microgate, OptoGate, Italy) that recorded jump height to the nearest 0.1 cm. Participants were instructed to complete the CMJ starting from a standing position, moving to a self-selected depth (without overpassing the knees joint with their hip), and to jump as high as possible (e.g., Román et al., 2018). A portable back and leg dynamometer (Takei Scientific Instruments Co., Ltd, Niigata-City, Japan) was used to measure IHE. Participants stood on a portable platform and pulled a handle connected with the platform via a chain. They were required to maintain a standard straight knees, back, and flexed hip. Following familiarization, participants were instructed to pull as hard and fast as possible after a 3 s countdown for 5 s (Coldwells et al., 1994). Handgrip strength was measured using a handgrip dynamometer (Takei, 5401, Takei Scientific Instruments, Japan). Once an optimal position was determined by sitting and holding the tested hand's elbow 90° flexed, participants' were instructed to "squeeze" as hard as possible for a 5 s duration (Massy-Westropp et al., 2011) only using the preferred (strongest) hand. Strong verbal encouragement was provided during the maximal strength tests. Each test was completed three times with the best attempt recorded for analysis.

A perceptual-cognitive video simulation test was used to examine the participants' decision-making skill based on a combination of tactical situations, which have been shown to be valid and reliable measures for PCE research in several sport environments (e.g., Kelly et al., 2020). Fifteen video clips were carefully chosen from live rugby match footage, filmed from different elevated angles to provide a wide-range view of the pitch. Following a few seconds of general build-up play, the screen unexpectedly frozen for 8 s prior to a critical decision-making moment. At this point, a question with four possible options appeared on the frozen action and participants had to select an answer on their response sheet before the next clip automatically began. As per examination conditions, participants were seated separately for ∼45 min and were unable to engage with each other. Participants overall score was ranked using percentiles (i.e., 90th; 75th; 50th; 25th; 10th) and then classified (i.e., 1 = excellent; 2 = good; 3 = average; 4 = low; 5 = poor) for analysis. The total accuracy of the participants' responses was recorded for analysis. Finally, each participant was assigned a birth quartile, which was calculated using their date of birth. The annual selection year was divided into four birth quartiles according to the English cut-off dates (birth quartile one [BQ1] = September, October, and November; BQ2 = December, January, and February; BQ3 = March, April, and May; BQ4 = June, July, and August; McCarthy and Collins, 2014).

These tests were designed as part of the 4 day performance summer camp in order to provide coaches and practitioners with objective data. Coaches and practitioners working for the Regional Academy were charged with selecting and deselecting the U15 players following the completion of the performance camp. These decisions are subjective in nature; although the objective data used as part of this study was provided to the coaches in order to facilitate their decisions. However, it is important to recognize that this data was not regularly collected by the Regional Academy prior to this study, thus coaches and practitioners may have a limited understanding in applying this data to their selection and deselection decisions.

Statistical Analysis

Data were checked for normal distribution using a Shapiro–Wilk test. Scores were then normalized using z-scores [$z = (x-\mu)/\delta$], where x is the raw score, μ is the population mean, and δ is the population standard deviation. A multivariate analysis of variance (MANOVA) was used to calculate difference among the combined anthropometric and physiological factors both between selected and non-selected participants and positions, whereas a one-way analysis of variance (ANOVA) was used to explore the differences for the cognitive test. A Cohen's d was also used to calculate the effect size of these factors. Cohen's d effect size was calculated as reported in previous literature (Cohen, 1988) with threshold values of 0.20 (small), 0.50 (medium), 0.80 (large), with corresponding 95% confidence intervals (CIs). A Welch's t-test was then conducted for the eight variables from the anthropometric, physiological, and cognitive factors to compare selected and non-selected participants, as well as position-specific comparisons (i.e., forwards vs. backs).

For birth quartiles, a chi-square (χ^2) goodness-of-fit was used to compare quartile distributions for selected participants against national norms (McHugh, 2013; Office for National Statistics, 2015). Since the χ^2 does not reveal the magnitude of difference between quartile distributions, a Cramer's V was also used to report the effect size (0.00 and under 0.10, negligible; 0.10 and under 0.20, weak; 0.20 and under 0.40, moderate; 0.40 and under 0.60, relatively strong; 0.60 and under 0.80, strong; 0.80 and under 1.00, very strong; Ferguson, 2009). Finally, a binary logistic regression was performed to model selected and non-selected participants, which comprised of multivariate analysis performance test only for statistically significant variables evidenced in the Welch's t-test or χ^2. The pseudo R-squared values, odds ratios (ORs), and 95% CIs were reported for each model. Significance was set for an α level of 0.05 with the statistical analysis conducted using IBM SPSS Statistics Version 24.

RESULTS

Results from the MANOVA and ANOVA showed that there was a significant difference between selected and non-selected players for both anthropometric ($P = 0.021$) and physiological ($P < 0.001$) characteristics. Further results from the Welch's t-tests revealed moderate to large differences between participants for body mass (selected = 69.9 ± 11.5 kg vs. non-selected = 63.5 ± 12.1 kg; $P = 0.022$, $d = 0.53$), handgrip strength (selected = 38.1 ± 7.2 kg vs. non-selected = 33.9 ± 8.0 kg; $P = 0.020$, $d = 0.52$), IHE (selected = 137.4 ± 22.6 kg vs. non-selected = 117.0 ± 23.8 kg; $P < 0.001$, $d = 0.87$), and 20 m sprint (selected = 3.33 ± 0.14 s vs. non-selected = 3.44 ± 0.21 s; $P < 0.001$, $d = 0.75$). When analysing groups based on position, selected forwards had greater IHE (144.3 ± 23.7 kg vs. 130.2 ± 12.6 kg; $P = 0.054$, $d = 0.77$) and 20 m sprint (3.40 ± 0.11 s vs. 3.53 ± 0.21 s; $P = 0.041$, $d = 0.71$) compared to non-selected forwards with large effect size differences. In comparison, selected backs had greater IHE (130.9 ± 20.2 kg vs. 108.3 ± 25.6 kg; $P < 0.001$, $d = 0.95$) and 20 m sprint (3.26 ± 0.13 s vs. 3.38 ± 0.18 s; $P = 0.011$, $d = 0.78$) compared to non-selected backs with large effect size differences. In addition, there was no significant differences between groups and positions for the perceptual-cognitive video simulation test. The descriptive statistics are reported in **Table 1**. The MANOVA for anthropometric and physiological factors and the ANOVA for cognitive factor are reported in **Table 2**. The Welch's *t*-test analysis is reported in **Table 3**.

Birth quartiles showed an higher proportion of those born in the first half of the year for selected participants (BQ1 = 28%, BQ2 = 38%, BQ3 = 10%, and BQ4 = 24%), although it was not statistically significant and had weak effect size [$\chi^2(3) = 4.62$, V = 0.28, $P = 0.206$]. Moreover, birth quartiles were significantly skewed for non-selected participants with a moderate effect size [$\chi^2(3) = 9.34$, V = 0.32, $P = 0.025$], whereby a higher proportion were born in the first half of the year (BQ1 = 38%, BQ2 = 29%, BQ3 = 27%, and BQ4 = 6%). With regards to position, both selected forwards [BQ1 = 36%, BQ2 = 36%, BQ3 = 14%, and BQ4 = 14%; $\chi^2(3) = 2.59$, V = 0.30, $P = 0.458$] and selected backs (BQ1 = 20%, BQ2 = 40%, BQ3 = 7%, and BQ4 = 33%; χ^2 (3) = 3.99, V = 0.36, $P = 0.262$) birth quartile's were skewed toward the first half of the year with moderate effect sizes, although it was not statistically significant. Likewise, both non-selected forwards [BQ1 = 33%, BQ2 = 33%, BQ3 = 28%, and BQ4 = 6%; $\chi^2(3) = 3.99$, V = 0.32, $P = 0.274$] and non-selected backs [BQ1 = 41%, BQ2 = 26%, BQ3 = 26%, and BQ4 = 7%; $\chi^2(3) = 5.96$, V = 0.33, $P = 0.113$] birth quartile's were skewed toward the first half of the year with moderate differences, although it was not statistically significant. The birth quartile results are reported in **Table 4**.

The multivariate logistic regression model explained between 21% (Cox and Snell R square) and 29% (Nagelkerke R square) of the variance in selection ($P = 0.001$). Only the 20 m sprint made a statistically significant contribution to the model that predicted selection. In general, 20 m sprint time explained 25.4% of the variance ($r^2 = 0.254$, $P = 0.039$). The multivariate logistic regression is reported in **Table 5**.

DISCUSSION

Key findings suggest that those who were selected into the Regional Academy were significantly heavier, stronger, and faster over 20 m compared to their non-selected peers, with effect sizes for anthropometric, physiological, and cognitive factors ranging from small to large. Further multivariate logistic regression also revealed that only the 20 m sprint was a significant predictor for selection; irrespective of playing position. With regards to birth quartile and the cognitive factor, there was no statistically significant differences reported for selected players, despite being overrepresented in the first two birth quartiles (i.e., BQ1 = 28% and BQ2 = 38%) compared to the second two birth quartiles (i.e., BQ3 = 10% and BQ4 = 24%).

When comparing anthropometric characteristics findings (i.e., body height and mass) with other selected RU players, some similarities and variations occur based on other studies across other nationality. As an example, Nutton et al. (2012) reported similar body mass in Scottish U15 RU players (175.0 ± 7.0 cm; 68.0 ± 11.4 kg), although they appeared to be considerably taller. The population of the present study was also shorter (171.8 ± 5.9 cm), as well as lighter (69.9 ± 11.5 kg), than South African U15 RU players (175.0 ± 6.0 cm, 75.9 ± 13.2 kg; Grobler et al., 2017). Whereas, they were taller and heavier when compared to their Brazilian U15 RU equivalents (169.7 ± 12.1 cm, 63.8 ± 10.9 kg; Kobal et al., 2016). In a recent systematic review by Owen et al. (2020), it was reported that body height and mass in U15 RU players ranged from 169.7 to 175.0 cm and 63.8 to 75.9 kg, respectively; which is in line with the present findings. Thus, it is important to consider national youth sport culture (e.g., individual talent pathways, sport popularity, and national population) during the TID process, since variations in anthropometric characteristics can be considerable (see Dimundo et al., 2021 for a review).

When analysing anthropometric data by position, both selected forwards (173.2 ± 3.6 cm, 77.2 ± 10.9 kg) and selected backs (170.5 ± 7.3 cm, 63.1 ± 7.2 kg) presented similar characteristics to those reported in a French U15 academy (forwards = 175.9 ± 7.0 cm, 72.5 ± 9.8 kg; backs = 169.5 ± 6.5 cm and 60.8 ± 8.2 kg; Sedeaud et al., 2013). Indeed, body mass was pivotal when distinguishing selected RU players (Dimundo et al., 2021) in both a South African academy (Pienaar et al., 1998) and in New Zealand at senior international level (Quarrie et al., 1996). Moreover, similar to the present study's findings, Barr et al. (2014) showed that body mass, but not height, differentiated U20 and international RU players. The variation in anthropometric measures among playing positions, although not statistically significant, align with the understanding that forwards and backs require diverse physical characteristics to perform key roles and cope with position-specific demands of the game (Owen et al., 2020). Together, these results demonstrate that anthropometric characteristics, and in particular body mass, appear to be an important factor to consider during TID in U15 RU players. However, although not verified in this current study, it is important to recognize that, as reported in a recent systematic review (Dimundo et al., 2021), body mass depends on multiple factors (e.g., fat mass, lean mass, bone mass, and water), whilst higher-level players usually possess lower fat mass than lean mass. As such, these findings offer an important benchmark for coaches and practitioners when selecting U15 RU players, as well as highlighting the differences between positions.

Strength parameters have been shown to differentiate by age, competition levels, and position of young RU players across various environments (e.g., Pienaar et al., 1998; van Gent and Spamer, 2005; Spamer and De la Port, 2006; Hansen et al., 2011; Grobler et al., 2017; Owen et al., 2020). In this current study, selected players reported superior handgrip strength when compared to non-selected players. Indeed, similar conclusions

TABLE 1 | Descriptive statistics for selected and non-selected U15 players.

Characteristic	Selected			Non-selected		
	Forwards (*n* = 14) mean ± SD	Backs (*n* = 15) mean ± SD	All players (*n* = 29) mean ± SD	Forwards (*n* = 18) mean ± SD	Backs (*n* = 27) mean ± SD	All players (*n* = 45) mean ± SD
Anthropometric						
Body mass (kg)	77.2 ± 10.9	63.1 ± 7.2	69.9 ± 11.5	71.3 ± 9.6	58.3 ± 10.9	63.5 ± 12.1
Height (cm)	173.2 ± 3.6	170.5 ± 7.3	171.8 ± 5.9	175.1 ± 7.0	166.9 ± 10.1	170.2 ± 9.8
Physiological						
Handgrip (kg)	40.6 ± 7.3	35.8 ± 6.6	38.1 ± 7.2	36.8 ± 6.3	31.9 ± 8.5	33.9 ± 8.0
IHE (kg)	144.3 ± 23.7	130.9 ± 20.2	137.4 ± 22.6	130.2 ± 12.6	108.3 ± 25.6	117.0 ± 23.8
10 m sprint (s)	1.41 ± 0.05	1.34 ± 0.06	1.37 ± 0.06	1.45 ± 0.10	1.38 ± 0.09	1.41 ± 0.10
20 m sprint (s)	3.40 ± 0.11	3.26 ± 0.13	3.33 ± 0.14	3.53 ± 0.21	3.38 ± 0.18	3.44 ± 0.21
CMJ (cm)	28.8 ± 4.7	33.2 ± 5.8	31.1 ± 5.7	27.3 ± 5.3	31.5 ± 5.8	29.8 ± 5.9
Cognitive						
Perceptual-cognitive video simulation test (au)	2.9 ± 1.3	3.5 ± 1.1	3.2 ± 1.2	3.2 ± 1.5	3.3 ± 1.3	3.2 ± 1.3
Birth Quartile						
BQ	2 ± 1	3 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1

Shows difference between selected and non-selected players and reports comparison among positions. SD, standard deviation; IHE, isometric hip extension; CMJ, countermovement jump; au, arbitrary unit; BQ, birth quartile.

TABLE 2 | MANOVA for the anthropometric and physiological factors and ANOVA for the cognitive factor.

Factor	Selected vs. non-selected forwards (*P*)	Selected vs. non-selected backs (*P*)	All selected vs. all non-selected (*P*)	Selected forwards vs. selected backs (*P*)
Anthropometric	0.031*	0.331	<0.021*	0.165
Physiological	0.246	0.020*	<0.001*	0.617
Cognitive	0.502	0.568	<0.989	0.453

*Significance set for P = 0.05; *a statistical significance of ≤0.05.*

have been reported in Portuguese (Vaz et al., 2019) and Scottish (Nutton et al., 2012) RU academy players, whereby it was suggested that handgrip strength should be one of the measures included in a battery of tests during the TID process since it was deemed a practical, safe, reliable, and valid method to detect a standard measure of strength in youths. Assessing force generating characteristics during the isomeric pull in RU has also been considered as a safe and useful tool to monitor progress across RU academies, since the technical requirement for these tests are less demanding compared to other traditional whole body strength tests (Darrall-Jones et al., 2015; Owen et al., 2020). Although not significant in multivariate logistic regression, all selected players in this study possessed greater handgrip and IHE measures than non-selected players, and selected forwards outperformed selected backs. However, it was not surprising that forwards possessed higher force than backs, since their playing-position requires them to produce higher isometric force during a game (Quarrie and Wilson, 2000). These results are in agreement with recent findings in RU (Owen et al., 2020), and demonstrate that whole body strength is an important factor to consider when approaching TID in RU due to its application in a multitude of key actions required in this contact sport (Till et al., 2020). Although results of this current study could have been influenced by an overrepresentation of relatively older participants and by the analysis of other characteristics of strength measures (i.e., relative strength), it also reveals how position-specific factors are already being influenced by physiological characteristics during initial entry into an academy at U15.

Sprint speed has been considered an important physiological quality in RU since it is associated with a range of performance outcomes, such as distance covered, evasion, and line and tackle breaks (Smart et al., 2014). It has been also used as one method to predict future talent in an Italian U16 RU academy (Fontana et al., 2017), indicating that it is worth monitoring this characteristic for optimal TID. In the current investigation, selected players possessed superior 20 m sprint times compared to non-selected players. Importantly, the 20 m sprint was the only predictive characteristic of selection in the current cohort. More specifically, those who possessed a faster 20 m sprint were up to 1.4 times more likely to be selected. A possible explanation for the importance of sprint speed in RU is that greater sprint characteristics have typically been correlated with greater momentum, which is believed to be fundamental in RU

TABLE 3 | *Z*-scores and Welch's *t*-tests for selected and non-selected players.

Characteristic	Selected *z*-score (mean ± SD)	Non-selected *z*-score (mean ± SD)	Welch's *t*-test (*P*)	Cohen's *d*
Body mass				
Forwards	0.32 ± 1.04	−0.25 ± 0.92	0.124	0.58 (−0.14, 1.28)
Backs	0.31 ± 0.73	−0.17 ± 1.10	0.099	0.49 (−0.15, 1.13)
Selected vs. non-selected	0.31 ± 0.88	−0.20 ± 1.02	0.022*	0.53 (0.06, 1.01)
Selected forwards vs. backs			0.982	0.00 (−0.72, 0.73)
Height				
Forwards	−0.19 ± 0.62	0.15 ± 1.21	0.320	−0.33 (−1.03, 0.37)
Backs	0.25 ± 0.79	−0.14 ± 1.09	0.199	0.39 (−0.25, 1.03)
Selected vs. non-selected	0.04 ± 0.74	−0.02 ± 1.14	0.761	0.06 (−0.40, 0.53)
Selected forwards vs. backs			0.100	−0.61 (−1.35, 0.14)
Handgrip				
Forwards	0.31 ± 1.05	−0.23 ± 0.92	0.133	0.56 (−0.16, 1.27)
Backs	0.31 ± 0.82	−0.17 ± 1.06	0.111	0.49 (−0.16, 1.12)
Selected vs. non-selected	0.31 ± 0.92	−0.19 ± 1.00	0.020*	0.52 (0.05, 1.00)
Selected forwards vs. backs			0.999	0.00 (−0.73, 0.73)
IHE				
Forwards	0.41 ± 1.23	−0.31 ± 0.65	0.054	0.77 (0.04, 1.49)
Backs	0.56 ± 0.78	−0.31 ± 0.99	<0.001*	0.95 (0.28, 1.60)
Selected vs. non-selected	0.49 ± 1.00	−0.31 ± 0.86	<0.001*	0.87 (0.38, 1.36)
Selected forwards vs. backs			0.707	−0.14 (−0.87, 0.59)
10 m sprint				
Forwards	−0.13 ± 0.32	0.10 ± 1.31	0.477	−0.23 (−0.93, 0.47)
Backs	−0.06 ± 0.44	0.03 ± 1.21	0.711	−0.09 (−0.73, 0.54)
Selected vs. non-selected	−0.09 ± 0.38	0.06 ± 1.24	0.432	−0.16 (−0.62, 0.31)
Selected forwards vs. backs			0.633	−0.18 (−0.91, 0.55)
20 m sprint				
Forwards	−0.38 ± 0.61	0.29 ± 1.15	0.041*	−0.71 (−1.42, 0.02)
Backs	−0.47 ± 0.73	0.26 ± 1.05	0.011*	−0.78 (−1.43, −0.12)
Selected vs. non-selected	−0.43 ± 0.66	0.27 ± 1.08	<0.001*	−0.75 (−1.23, −0.27)
Selected forwards vs. backs			0.709	0.14 (−0.59, 0.87)
CMJ				
Forwards	0.17 ± 0.94	−0.12 ± 1.05	0.411	0.29 (−0.41, 0.99)
Backs	0.18 ± 0.99	−0.10 ± 1.01	0.381	0.28 (−0.35, 0.92)
Selected vs. non-selected	0.17 ± 0.95	−0.11 ± 1.01	0.222	0.29 (−0.18, 0.76)
Selected forwards vs. backs			0.965	−0.02 (−0.75, 0.71)
Perceptual-cognitive video simulation test				
Forwards	−0.14 ± 0.93	0.10 ± 1.07	0.499	−0.24 (−0.94, 0.46)
Backs	0.12 ± 0.90	−0.06 ± 1.06	0.546	0.19 (−0.45, 0.82)
Selected vs. non-selected	0.00 ± 0.91	0.00 ± 1.05	0.981	0.00 (−0.47, 0.46)
Selected forwards vs. backs			0.455	−0.28 (−1.01, 0.45)

*Shows difference between selected and non-selected players and reports comparison among positions. In the column headings indicate overall effects (significance set for P = 0.05). Post-hoc and Cohen's d effect size (90% confidence interval). IHE, isometric hip extension; CMJ, countermovement jump; *a statistical significance of ≤0.05.*

(Darrall-Jones et al., 2016; Jones et al., 2018). Thus, although momentum was not considered in this research, it is not surprising that fastest players were selected in the current academy squad. In addition, the present investigation found speed differences among playing positions. For instance, although 20 m sprint speed was an important factor for all players to possess, this was position-dependent whereby backs were generally faster than forwards. Therefore, in agreement to Jones et al.'s (2018) findings, 20 m sprint time can be considered one of the most valuable measures to include in a battery of tests when coaches aim to optimize TID during selection into their U15 cohort.

Cognitive skills are important factors to consider when selecting athletes in different sports (Mann et al., 2007). Although previous research in RU has suggested that superior cognitive skills differentiate playing levels (e.g., Farrow et al., 2010;

TABLE 4 | Birth quartile distributions by position vs. national norms.

Cohort	BQ1 (*n*) %	BQ2 (*n*) %	BQ3 (*n*) %	BQ4 (*n*) %	Total (*n*) %	X^2 (df = 3)	Cramer's V	*P*	Q1 vs. Q4 (OR, 95% CI)	Q2 vs. Q4 (OR, 95% CI)	Q3 vs. Q4 (OR, 95% CI)
Selected forwards	5 (35.7%)	5 (35.7%)	2 (14.3%)	2 (14.3%)	14 (100%)	2.59	0.30	0.453	2.49 (0.27–22.55)	2.59 (0.28–23.70)	1.03 (0.08–12.02)
Selected backs	3 (20%)	6 (40%)	1 (6.7%)	5 (33.3%)	15 (100%)	3.99	0.36	0.267	0.59 (0.07–4.49)	1.24 (0.19–0.01)	0.20 (0.01–2.72)
Selected forwards and backs	8 (27.6%)	11 (37.9%)	3 (10.4%)	7 (24.1%)	29 (100%)	4.62	0.28	0.206	1.14 (0.27–4.81)	1.63 (0.40–6.62)	0.44 (0.08–2.41)
Non-selected forward	6 (33.3%)	6 (33.3%)	5 (27.8%)	1 (5.6%)	18 (100%)	3.88	0.32	0.274	5.99 (0.50–71.66)	6.23 (0.51–75.07)	5.15 (0.41–63.63)
Non-selected backs	11 (40.7%)	7 (25.9%)	7 (25.9%)	2 (7.5%)	27 (100%)	5.96	0.33	0.113	5.49 (0.87–34.60)	3.63 (0.54–24.31)	3.60 (0.54–24.10)
Non-selected forwards and backs	17 (37.8%)	13 (28.9%)	12 (26.7%)	3 (6.6%)	45 (100%)	9.34	0.32	0.025*	5.65 (1.29–24.74)	4.50 (1.00 –20.24)	4.12 (0.91–18.68)

*BQ1 = September, October, and November; BQ2 = December, January, and February; BQ3 = March, April, and May; BQ4 = June, July, and August. Birth quartile (BQ1–BQ4) distribution by positions, total number of players, and comparisons against national norm with odd ratio (OR) set at 95% of confidence interval (CI), significance set for P = 0.05; *denotes a statistical significance of ≤0.05.*

Chiwaridzo et al., 2019a,b; den Hollander et al., 2019; Chiwaridzo et al., 2020; Runswick et al., 2020), results from this study did not report any statistical difference between selected and non-selected players. The outcomes of the present investigation could be justified by the fact that perceptual-cognitive qualities in U15 RU players may not have peaked at this stage of development. As an example, players may not have accumulated an adequate volume of hours in practice activities to develop athlete functionality at this entry level (Rothwell et al., 2020). Another explanation for this outcome could be due to the fact that coaches may have been focused on (and perhaps biased by) anthropometrical and physiological characteristics possessed by participants. In contrast, however, present findings on positional differences align with those of Runswick et al. (2020), whereby no statistical differences were reported in anticipation skills between forwards and backs. In summary, perceptual-cognitive skills remain an inconclusive measure for selection into a RU academy. Further study is encouraged to explore the implications of perceptual-cognitive skills on selection into RU academies, as well as incorporating a range of technical and psychosocial characteristics in holistic TID research methodologies.

Based on the common prevalence of RAEs in male RU, it was not surprising that there was an overrepresentation of selected players born between September and February in this current investigation (although this was only statistically significant for non-selected players). Specifically, the birth distribution revealed that almost twice as many players were selected from the first half of the year ($n = 19$; 66%) when compared to the second half of the year ($n = 10$; 34%). Non-selected players were significantly more likely to be born in the first half of the year ($n = 30$; 67%) compared to the second half of the year ($n = 15$; 33%). The percentages obtained reflect those reported in U7–U19 Welsh recreational RU clubs (BQ1 = 29% vs. BQ4 = 22%; Lewis et al., 2015), U13–U16 English regional representative squads (BQ1 = 38% vs. BQ4 = 10%; Roberts and Fairclough, 2012), English Regional Academies (BQ1 = 42% vs. BQ4 = 8%; McCarthy and Collins, 2014), and senior international levels (BQ1 = 32% vs. BQ4 = 20%; Kearney, 2017). Together, these results suggest that early born players may have an advantage over later born athletes during the initial phase of the TID process, since both selected and non-selected players are overrepresented. To be specific, the entry point into the Regional Academy appears to be biased toward their invitations to attend the performance camp; regardless of subsequent (un)successful selection (BQ1 and BQ2 = 66.2%). Moreover, the selection of relatively older players may be due to the fact that older players are likely to be more mature than younger ones (see Cobley et al., 2009). In U15 players, this may have resulted in relatively older players being faster and stronger than their relatively younger counterparts due to being less-developed. As such, Regional Academies are encouraged to explore alternative approaches to athlete selection (e.g., age-ordered shirt numbering; selection quotas; avoiding early deselection; flexible chronological approach) and group banding policies (e.g., age and anthropometric bands; bio-banding; playing-up and playing-down; see Webdale et al., 2020 for a review). Indeed, these could offer useful evidence-based guidelines in the future for other organizations and

TABLE 5 | Main variables for multivariate logistic regression for selection and positions.

Cohort	Predictor	Coefficient β	SE	Wald's χ2	Odds Ratio (95% CI)	Log likelihood	Cox and Snell R^2	Nagelkerke R^2
Forwards: selected vs. non-selected						−18.87	0.198	0.265
	IHE	0.714	0.445	χ2(1) = 2578, *P* = 0.108	0.490 (−1.585; 0.158)			
	20 m sprint	−0.741	0.503	χ2(1) = 2174, *P* = 0.140	2.099 (−0.244; 1.727)			
	Constant	−0.319	0.405	χ2(1) = 0.620, *P* = 0.431	1.376 (−0.475; 1.113)			
Backs: selected vs. non-selected						−25.44	0.209	0.287
	IHE	0.884	0.499	χ2(1) = 3.131, *P* = 0.077	0.413 (−1.863; 0.095)			
	20 m sprint	−0.557	0.495	χ2(1) = 1264, *P* = 0.261	1.745 (−0.414; 1.528)			
	Constant	−0.820	0.400	χ2(1) = 4.200, *P* = 0.040	2.270 (0.036; 1.604)			
All: selected vs. non-selected						−40.74	0.212	0.287
	Body mass	0.378	0.370	χ2(1) = 1.042, *P* = 0.307	1.459 (0.706; 3.014)			
	Handgrip	0.282	0.391	χ2(1) = 0.522, *P* = 0.470	0.754 (0.351; 1.622)			
	IHE	0.661	0.399	χ2(1) = 2.741, *P* = 0.098	1.936 (0.886; 4.232)			
	20 m sprint	−0.805*	0.391	χ2(1) = 4.244, *P* = 0.039*	0.447 (0.208; 0.962)			
	Constant	−0.621	0.288	χ2(1) = 4.651, *P* = 0.031	1.861 (0.057; 1.186)			

*SE, standard error; IHE, isometric hip extension; 20 m sprint, sprinting time; *a statistical significance of ≤0.05.*

coaches to adopt practical solutions to RAEs as part of their TID procedures.

Limitations and Future Directions

There are often methodological challenges when researching high-performance youth populations. In the context of this current study, although a relatively large representative sample of participants were examined (i.e., one of only fourteen Regional Academies across the country), the sub-analysis for position-specific study (i.e., forwards and backs) could have been influenced due to the sample size. It is also important to recognize that this study is susceptible to the individual academy's approach to TID, thus this sample may not be representative of all Regional Academy selection decisions. There may also be the case that the assessment of perceptual-cognitive skills in this current study could have been influenced by its sensitivity, possibly influencing the final results. Body mass was only recorded in kg and there was not the possibility to detect other important information such as fat and lean mass due to time constraints. Moreover, as the maturation status of the players was not assessed, it is not known to what extent this impacted selection. In addition, this study did not include the measurement of other important characteristics previously shown to be significant predictors of performance and selection (i.e., technical and psychosocial; Dimundo et al., 2021). Authors did not have information regarding participants' previous playing experience, which could have provided a better context of the population. The present findings may help selectors to refine their TID process, however, their selection reflects both their subjective perspectives and the estimated players' potential. Finally, it is also important to note that this study is cross-sectional in design, as such it does not take into account the dynamic, longitudinal nature of athlete development.

Future research is encouraged to include a more holistic and longitudinal protocol when assessing Regional Academy selection. As an example, longitudinal investigations should consider collecting the examined variables from a wider population by (a) including other performance factors (i.e., technical and psychosocial), and (b) expand performance indicators (i.e., including additional factors such as momentum), to study the ecological dynamic characteristics of the TID process (Till et al., 2013, 2015). The complex nature of the TID process is multitudinous by nature. Thus, selectors should act with caution when interpreting these outcomes, and are recommended not to base their selections *solely* on anthropometric and physiological qualities, and instead use these objective measures to complement their performance camps and decision-making processes on selection. Moreover, literature regarding athlete development suggests that due to greater physical characteristics being associated with early development, coaches should consider benchmarks based on biological age rather than chronological age (Malina et al., 2019; Kelly et al., 2021b). Lastly, as reported by Huijgen et al. (2014), coaches cognitive bias should be taken into account when examining players on physiological and technical variables for future researches in TID.

CONCLUSION

This is the first study that has incorporated a multidisciplinary research design to compare selected and non-selected U15 RU players at an English Premiership Regional Academy. It appears anthropometric and physiological qualities are more predictive of selection when compared to cognitive characteristics and birth quartiles. Specifically, it is suggested that body mass, strength, and speed are part of a battery of tests that formulate part of the TID process during selection into Regional Academies. Moreover, Position-specific differences should also be considered also during early stages of TID. In addition, although birth quartile distribution was only statistically significant in the non-selected cohort, coaches and practitioners employed in youth RU should consider this as part of a holistic selection framework so potential talent is not missed. Future research is encouraged to adopt a multidimensional and longitudinal approach when investigating TID in RU, to build on this current study and better understand the selection processes in Regional Academies.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Birmingham City University via the Health, Education, and Life Sciences Research Ethics Committee. Written informed consent to participate in this study was provided by the participants' legal guardian/next of kin.

AUTHOR CONTRIBUTIONS

FD and AK contributed to conception and design of the study. FD organized the database and performed the statistical analysis. FD, AM, and AK contributed to the first draft of the manuscript. All authors contributed to manuscript revisions and approved the submitted version.

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Olympic Sports Science—Bibliometric Analysis of All Summer and Winter Olympic Sports Research

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Introduction: The body of scientific literature on sports and exercise continues to expand. The summer and winter Olympic games will be held over a 7-month period in 2021–2022.

Objectives: We took this rare opportunity to quantify and analyze the main bibliometric parameters (i.e., the number of articles and citations) across all Olympic sports to weigh and compare their importance and to assess the structure of the "sport sciences" field. The present review aims to perform a bibliometric analysis of Olympic sports research. We quantified the following topics: (1) the most investigated sports; (2) the main journals in which the studies are published; (3) the main factors explaining sport-specific scientific attractiveness; (4) the influence of being in the Olympic programme, economic weight, and local influences on research output; and (5) which research topic is the most investigated across sports

Methods: We searched 116 sport/exercise journals on PubMed for the 40 summer and 10 winter Olympic sports. A total of 34,038 articles were filtered for a final selection of 25,003 articles (23,334 articles on summer sports and 1,669 on winter sports) and a total of 599,820 citations.

Results and Discussion: Nine sports [football (soccer), cycling, athletics, swimming, distance & marathon running, basketball, baseball, tennis, and rowing] were involved in 69% of the articles and 75% of the citations. Football was the most cited sport, with 19.7 and 26.3% of the total number of articles and citations, respectively. All sports yielded some scientific output, but 11 sports (biathlon, mountain biking, archery, diving, trampoline, skateboarding, skeleton, modern pentathlon, luge, bobsleigh, and curling) accumulated a total of fewer than 50 publications. While ice hockey is the most prominently represented winter sport in the scientific literature, winter sports overall have produced minor scientific output. Further analyses show a large scientific literature on team sports, particularly American professional sports (i.e., baseball, basketball, and ice hockey) and the importance of inclusion in the Olympic programme to increasing scientific interest in "recent" sports (i.e., triathlon and rugby sevens). We also found local/cultural influence on the occurrence of a sport in a particular "sport sciences" journal. Finally, the

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relative distribution of six main research topics (i.e., physiology, performance, training and testing, injuries and medicine, biomechanics, and psychology) was large across sports and reflected the specific performance factors of each sport.

Keywords: citations, publication, sport sciences, summer Olympic sports, winter Olympic sports

INTRODUCTION

The Olympic sports (https://olympics.com/en/sports/) bring together a large and diverse range of human abilities that extend far beyond the Olympic motto, "*Citius—Altius—Fortius*" (i.e., Faster—Higher—Stronger"), and outstanding genetic, physical, technical and mental skills are required to reach an Olympic podium. It is therefore not surprising that behind each athlete is an interdisciplinary team of experts/scientists (Hodson, 2021). Elite sports performance has long been a fascinating field of research for scientists. The 1922 Nobel Prize in Physiology or Medicine, awarded to Sir A. V. Hill and his work on the best middle-distance runners of his time, provides a perfect example of ground-breaking research originating from related questions (Hill, 1925). Over the last two decades, the "sport sciences" field has massively expanded, as evidenced by the continuously growing number of journals (e.g., 85 journals in 2021 vs. 58 in 1998 in the "sport sciences" category of the Incites journal citations report—https://jcr.clarivate.com). The original definition of sport sciences as "*the study and application of scientific principles and techniques to improve sporting performance*" (Lippi et al., 2008) has become too narrow, and researchers in different scientific fields (e.g., antidoping sciences, biomechanics, physiology, nutrition, injury prevention and rehabilitation, psychology, pedagogy, management and marketing, history, sociology and many biomedical fields, including preventive medicine and oncology) (Millet and Giulianotti, 2019) are producing an enormous body of research related to exercise and sports. However, to our knowledge, there has been no comprehensive analysis of the "sport sciences" field and no comparison of the sport-specific scientific literature across all Olympic sports. Currently available bibliometric analyses are limited to the most cited articles in sport and exercise medicine (Knudson, 2011; Khatra et al., 2021) or specifically concern a single sport, such as football (soccer) (Brito et al., 2018), or a specific scientific field (e.g., sports economics, sports management or sociology) (Santos and Garcia, 2011; Shilbury, 2011; Gau, 2013).

In 1992, the summer (Barcelona) and winter (Albertville) Olympic games took place for the last time in the same year. Due to the COVID-19 pandemic, the two games (Tokyo 2020 Summer Olympic Games between 23 July and 8 August 2021 and Beijing 2022 Winter Olympics between 4 and 20 February 2022) will now be organized within a 7-month timeframe. This may be an occasion to review the science across all summer and winter Olympic sports.

The present review aims to perform a bibliometric analysis of Olympic sports research. We quantified the following topics: (1) the most investigated sports; (2) the main journals in which the studies are published; (3) the main factors explaining sport-specific scientific attractiveness; (4) the influence of being in the Olympic programme, economic weight, and local influences on research output; and (5) which research topic is the most investigated across sports.

METHODS

The data were obtained by a search in PubMed followed by a search conducted in Web of Science (Clarivate Analytics, USA). First, we selected 116 "sport sciences" journals (**Table 1**), including 85 journals of the "*sport sciences*" category in the Incites journal citations report (Clarivate Analytics, USA); then, we expanded the search to other journals with "exercise" or "sport" in the title. Second, we chose to limit the analysis to sports that are currently in the Olympic programme for Tokyo 2020 (**Table 2A**) and Beijing 2022 (**Table 2B**). This list of sports does not contain sports to be included in the Paris 2024 Olympic Games or sports eliminated from the Olympic programme. We split some sports into subdisciplines (e.g., athletics and distance running and marathon or walking; Alpine skiing and Nordic skiing; cycling and mountain biking) when their natures were too different and sufficient data were available.

The search was performed on 4–5 June 2021 on article titles, and the inclusion and exclusion items are displayed in **Table 3**. Searching for only the sports or athletes (e.g., judo and judoka) in all these "sport sciences" journals would have yielded 103,164 articles, with many of them irrelevant in terms of our goals. By selecting only articles related to the selected sports—e.g., excluding animal, paralympic, and ultra-sports and fulfilling the inclusion and exclusion (e.g., "American football" for "football" or "water skiing" for "alpine skiing" or "athletes") criteria (see **Tables 3A,B** for the specific criteria of each sport), we reduced the final number of articles to 25,003 (23,334 articles on summer sports and 1,669 on winter sports). If two different sports were mentioned in the article title, the article was allocated to both. All articles were double-checked (GPM and FB) for conformity with the selection criteria. Auto citations were not removed from this analysis.

On 15 June, we performed a complete search for all these articles on Web of Science (Clarivate Analytics, USA). Basic information, including author(s), source journal, publication year, citations per year, and the total number of citations as well as keywords, was extracted. For each sport, the articles were listed based on citation frequency from highest to lowest, and the main metrics were averaged for the top 10 articles in each sport.

We compared the dates of the Olympic debut and the first publication for each sport (**Figure 1**) and for the "recent" Olympic sports (i.e., with an Olympic debut in 1998 or later)

TABLE 1 | List of the journals.

1. ACSM Health & Fitness Journal
2. Adapted Physical Activity Quarterly
3. American Journal of Physical Medicine & Rehabilitation
4. American Journal of Sports Medicine
5. Applied Physiology Nutrition and Metabolism
6. Archives of Budo
7. Archives of Physical Medicine and Rehabilitation
8. Arthroscopy-The Journal of Arthroscopic and Related Surgery
9. Biology of Sport
10. BMC Sports Science Medicine and Rehabilitation
11. British Journal of Sports Medicine
12. British Medical Journal Open Sport Exercise
13. Canadian Journal of Applied Physiology
14. Clinical Biomechanics
15. Clinical Journal of Sport Medicine
16. Clinics in Sports Medicine
17. Current Sports Medicine Reports
18. Deutsche Zeitschrift fur Sportmedizin
19. European Journal of Applied Physiology
20. European Journal of Sport Science
21. European Sport Management Quarterly
22. Exercise and Sport Sciences Reviews
23. Exercise Immunology Review
24. Frontiers in Sports and Active Living
25. Gait & Posture
26. High Altitude Medicine & Biology
27. Human Movement Science
28. International Journal of Performance Analysis In Sport
29. International Journal of Sport Finance
30. International Journal of Sport Nutrition and Exercise Metabolism
31. International Journal of Sport Psychology
32. International Journal of Sports Marketing & Sponsorship
33. International Journal of Sports Medicine
34. International Journal of Sports Physiology and Performance
35. International Journal of Sports Science & Coaching
36. International Journal of the History of Sport
37. International Review for The Sociology of Sport
38. International Review of Sport and Exercise Psychology
39. Isokinetics and Exercise Science
40. Japanese Journal of Physical Fitness and Sports Medicine
41. Journal of Aging and Physical Activity
42. Journal of Applied Biomechanics
43. Journal of Applied Physiology
44. Journal of Applied Sport Psychology
45. Journal of Athletic Training
46. Journal of Clinical Sport Psychology
47. Journal of Electromyography and Kinesiology
48. Journal of Exercise Science & Fitness
49. Journal of Hospitality Leisure Sport & Tourism Education
50. Journal of Human Kinetics
51. Journal of Motor Behavior
52. Journal of Orthopaedic & Sports Physical Therapy
53. Journal of Orthopaedic Trauma
54. Journal of Rehabilitation Medicine
55. Journal of Science and Medicine in Sport
56. Journal of Shoulder and Elbow Surgery
57. Journal of Sport & Exercise Psychology
58. Journal of Sport & Social Issues
59. Journal of Sport and Health Science
60. Journal of Sport History
61. Journal of Sport Management
62. Journal of Sport Rehabilitation
63. Journal of Sports Chiropractic & Rehabilitation
64. Journal of Sports Economics
65. Journal of Sports Medicine and Physical Fitness

(Continued)

TABLE 1 | Continued

66. Journal of Sports Science and Medicine
67. Journal of Sports Sciences
68. Journal of Sports Traumatology and Related Research
69. Journal of Strength and Conditioning Research
70. Journal of Teaching in Physical Education
71. Journal of The International Society of Sports Nutrition
72. Journal of The Philosophy of Sport
73. Kinesiology
74. Knee
75. Knee Surgery Sports Traumatology Arthroscopy
76. Measurement in Physical Education and Exercise Science
77. Medicina Dello Sport
78. Medicine and Science in Sports and Exercise
79. Motor Control
80. Operative Techniques in Sports Medicine
81. Orthopaedic Journal of Sports Medicine
82. Pediatric Exercise Science
83. Physical Education and Sport Pedagogy
84. Physical Therapy in Sport
85. Physician and Sportsmedicine
86. Physikalische Medizin Rehabilitationsmedizin Kurortmedizin
87. PM&R
88. Proceedings of The Institution of Mechanical Engineers Part P-Journal of Sports Engineering and Technology
89. Psychology of Sport and Exercise
90. Quest
91. Research in Sports Medicine
92. Research Quarterly for Exercise and Sport
93. Research Quarterly for Exercise and Sport
94. Revista Brasileira De Medicina Do Esporte
95. Revista Internacional De Medicina Y Ciencias De La Actividad Fisica Y Del Deporte
96. Scandinavian Journal of Medicine & Science in Sports
97. Science & Sports
98. Sociology of Sport Journal
99. South African Journal for Research in Sport Physical Education and Recreation
100. Sport Education and Society
101. Sport Exercise and Performance Psychology
102. Sport in Society
103. Sport Management Review
104. Sport Marketing Quarterly
105. Sport Psychologist
106. Sport Science Review
107. Sports (Basel)
108. Sports Biomechanics
109. Sports Exercise and Injury
110. Sports Health-A Multidisciplinary Approach
111. Sports Medicine
112. Sports Medicine and Arthroscopy Review
113. Sportverletzung-Sportschaden
114. Strength and Conditioning Journal
115. Wilderness & Environmental Medicine
116. Zeitschrift fur Sportpsychologie

The 85 journals of the Clarivate^{TM} Incites Journal Citation Reports "Sport Sciences" category are displayed in bold.
https://jcr.clarivate.com.

to display the potential influence of being in the Olympic programme on the scientific interest in a sport (**Figure 2**).

We also compiled the keywords related to six main research topics [1. Physiology; 2. Performance; 3. Training and testing (i.e., fitness, testing, training); 4. Injuries and medicine (i.e.,

TABLE 2 | Summer **(A)** and Winter **(B)** Olympic sports (https://olympics.com/en/sports).

A. SUMMER SPORTS
117. Archery
118. Athletics
119. Badminton
120. Baseball
121. Basketball
122. Boxing
123. Canoe-Kayak
124. Cycling
125. Diving
126. Equestrian
127. Fencing
128. Field Hockey
129. Football
130. Golf
131. Gymnastics
132. Handball
133. Judo
134. Karate
135. Marathon
136. Modern Pentathlon
137. Mountain Biking
138. Rowing
139. Rugby Sevens
140. Sailing
141. Shooting
142. Skateboarding
143. Softball
144. Sport Climbing
145. Surfing
146. Swimming
147. Table Tennis
148. Taekwondo
149. Tennis
150. Trampoline
151. Triathlon
152. Volleyball
153. Walking
154. Waterpolo
155. Weightlifting
156. Wrestling
B. WINTER SPORTS
157. Alpine—Freestyle Skiing
158. Biathlon
159. Bobsleigh
160. Curling
161. Ice Hockey
162. Luge
163. Nordic Skiing
164. Skating
165. Skeleton
166. Snowboard

"Marathon" and "Walking" (Athletics) as well as "Mountain biking" (Cycling) are displayed separately.
Skiing is displayed in 2 separated categories: "Alpine and freestyle skiing" and "Nordic skiing."

doping, injuries, medicine, rehabilitation); 5. Biomechanics (i.e., biomechanics, movement, motor control, equipment); 6. Psychology] for each sport. We display the top 5 most cited articles for every summer (**Table 4**) and winter (**Table 5**) Olympic sport.

RESULTS

The bibliometric analysis was performed on 50 Olympic sports or disciplines in 116 "sport sciences" journals and led to the selection of 25,003 articles with a total number of ∼600,000 citations.

There is a large range of articles and citations across sports (**Figure 3**). Nine sports (football, cycling, athletics, swimming, distance & marathon running, basketball, baseball, tennis, and rowing) were involved in 69% of the articles and 75% of the citations. Football (soccer) was the most cited sport, with 19.7 and 26.3% of the total numbers of articles and citations, respectively. Scientific research has been published on all sports, but 11 sports (biathlon, mountain biking, archery, diving, trampoline, skateboarding, skeleton, modern pentathlon, luge, bobsleigh, and curling) accumulated a total of fewer than 50 publications. While ice hockey is the most prominently represented winter sport in the scientific literature, winter sports overall have produced minor scientific output.

The analysis of the level and depth of the 10 most cited articles in every sports confirms this discrepancy across sports (**Figure 4**). This analysis confirms the results in terms of total publications across sports (**Figure 3**). Some sports (e.g., basketball and baseball) have highly cited articles (i.e., based on the average number of citations of the 10 most cited articles). This is also the case for handball, which has a relatively low number of citations (**Figure 3**) but a few highly cited articles (**Figure 4**).

Next, we analyzed the distribution of "Olympic sport sciences" publications across journals. This investigation revealed that only a small number of journals have published the greatest part of such articles. Merely six journals (*J Strength Cond Res*, 10.0%; *J Sports Sci*, 7.7%; *J Sports Med Phys Fitness*, 6.2%; *Br J Sports Med*, 5.5%; *Int J Sports Med*, 5.3%; and *Med Sci Sports Exerc*, 5.2%) of the 116 included in our search had published 40% of all publications (**Figure 5**). Some factors (including the nature of the sport as well as geographical and cultural factors and the composition of the editorial board), however, seem to have influenced the ratio of articles on specific sports appearing in different journals. For example, baseball articles have been published mainly in orthopedic or "sports medicine" journals (1. *Am J Sports M*ed; 2. *J Shoulder Elbow Surgery*, and 3. *Orthop J Sports Med*) while basketball articles were published in conditioning or "sport sciences" journals (1. *J Strength Cond Res*; 2. *J Sports Sci*, and 3. *J Sports Med Phys Fitness*). Tennis articles are overrepresented in *Br J Sports Med*, and Nordic skiing articles in *Scand J Med Sci Sports.*

Finally, the distribution of different research topics (i.e., physiology, performance, training and testing, injuries and medicine, biomechanics, and psychology) varies largely among sports (**Figure 6**).

DISCUSSION

The present bibliometric analysis is the first to quantify the bibliometric across all summer and winter Olympic sports. This comprehensive review provides interesting outcomes that are summarized briefly here and discussed afterwards:

TABLE 3 | Inclusion and exclusion criteria in the search for **(A)** all sports, **(B)** the summer, and **(C)** winter Olympic sports.

A. ALL SPORTS	
Exclusion topic	**Exclusion items**
Animal	Rats, mice, mouse, dog, cat, horse, fish
Paralympic	Disabl#, paral#, wheelchair
Ultra-sport	Ultra
Retracted articles	Retract#

Sports	**Inclusion items**	**Nb articles**	**Exclusion**	**Nb articles**
B. SUMMER SPORTS				
Archery	Archery, archer	43		43
Athletics	athletics, decathlon, decathlete, heptathlon, heptathlete, track and field, track-and-field javelin, shot put, shot-put, shot putter, high jump, long jump, discus throw, triple jump, pole vault, pole-vault, pole-vaulter, hammer throw, steeple chase, hurdle, hurdler, sprint, sprinter, sprinting, relay	8,492	Athlete, cycling, cyclist, swim, ski, skier, football, soccer, rugby, repeated-sprint	1,586
Badminton	Badminton	143		143
Baseball	Baseball	953		949
Basketball	Basketball, basket player	1,064		1,042
Boxing	Boxing, boxer	225		223
Canoe-Kayak	Canoe, kayak, canoeist, kayaker, kayakist, paddler	184		180
Cycling	Cycling, cyclist, bike, bicycle, bicycling, BMX	3,809	Triathlon, triathlete, mountain bike	3,550
Diving	Diving, diver, springboard	435	Breath-hold, scuba, apnea, football, pearl diver, decompression	52
Equestrian	Equestrian, horseman, horsemen, horse rider, horse-rider, horse riding, horse-riding, equitation	58		52
Fencing	Fencing, fencer	90		90
Field Hockey	Field hockey, hockey	166	ice	167
Football	Football, soccer, foot player, footballer	5,444	American football, league football, NFL, Gaelic football, Australian rules football, rugby football, quarterback	4,937
Golf	Golf, golfer	491		491
Gymnastics	Gymnastics, gymnastic, gymnast, floor exercise, horizontal bar, parallel bars, pommel horse, uneven bars, balance beam	429		428
Handball	Handball, handballer	440		440
Judo	Judo, judoka	262		261
Karate	Karate, karateka	114		113
Marathon—running	Marathon, marathoner, running, runner, middle-distance, long-distance	2,030	all sports but running	1,499
Modern pentathlon	Pentathlon, pentathlete	12		12
Mountain biking	Mountain bike, mountainbike, mountain biker	70		64
Rowing	Rowing, rower	678		673
Rugby sevens	Rugby sevens	89		89
Sailing	Sailing, sailer, sailor, windsurfing, windsurfer	110		109
Shooting	Shooting, shooter, riffle	135	football, soccer, handball, basketball	55
Skateboarding	Skateboarding, skateboarder	27		27
Softball	Softball	123		122
Sport Climbing	climbing, climber	512	step, stair, ladder, altitude, cyclist, cycling, mountaineer, mountaineering	338
Surfing	Surfing, surf, surfer	124	windsurf	100
Swimming	Swimming, swimmer, butterfly, backstroke, freestyle, free style, breaststroke, front crawl, frontcrawl, front-crawl	2,268		2,009
Table Tennis	Table tennis	90		90
Taekwondo	Taekwondo	159		159

(Continued)

TABLE 3 | Continued

Sports	Inclusion items	Nb articles	Exclusion	Nb articles
Tennis	Tennis	1,054	Table tennis	954
Trampoline	Trampoline	43		41
Triathlon	Triathlon, triathlete	548	Ironman	425
Volleyball	Volleyball, volley-ball, volley ball, beach volley, volley player	606		602
Walking	Walking, walker	323		319
Waterpolo	Waterpolo, water polo, water-polo	150		136
Weightlifting	Weightlifting, weightlifter	264		264
Wrestling	Wrestling, wrestler	405		400
C. WINTER SPORTS				
Alpine—freestyle skiing	Alpine skiing, alpine ski, alpine skier, freestyle skiing, freestyle ski, freestyle skier, giant slalom, slalom	300	Canoe, kayak, water ski, water-ski	294
Biathlon	Biathlon, biathlete	47		47
Bobsleigh	Bobsleigh, bobsled	7		7
Curling	Curling, curler	8		8
Ice Hockey	Ice hockey, ice-hockey, NHL, National Hockey League	540		540
Luge	Luge	6		6
Nordic skiing	Cross-country ski, cross-country skier, cross-country skiing, Crosscountry ski, crosscountry skier, ski jumping, ski jumper, Nordic combined	369		369
Skating	Ice skating, ice skater, Ice-skating, ice-skater short track, skating, skate, figure skate, speed skating, speed skater	380	roller	334
Skeleton	Skeleton	17		12
Snowboard	Snowboard, snowboarding, snowboarder	152		152

The number of articles found with the inclusion criteria and with the subsequent exclusion criteria and "manual cleaning" of the database are displayed.

1. There is a large difference in scientific output among sports, with nine sports representing 75% of the citations and 11 having a total of fewer than 50 associated publications.
2. Football (soccer) is by far the leading Olympic sport in terms of bibliometrics.
3. Team sports, particularly American professional sports (i.e., baseball, basketball, ice hockey), generate high scientific interest.
4. Overall, winter sports generate minor scientific output.
5. Most articles have been published in a limited number of journals.
6. Whether the inclusion of a sport in the Olympic programme translates into an increase in scientific publications remains unclear.
7. We also report some influence of local/cultural factors and/or of editorial board composition on the importance of a given sport in a given journal.
8. Finally, the distribution of articles among six main research topics (i.e., physiology, performance, training and testing, injuries and medicine, biomechanics, and psychology) highlights the (scientific) performance determinants of each sport.

Large Differences Between Sports

To our knowledge, there has been no comprehensive analysis and comparison of the largely different physical demands across all Olympic sports since the multifactorial determinants of performance within and across all Olympic sports render such analysis difficult. For example, curling and shooting have little in common with boxing, triathlon, or freestyle skiing. A quantitative comparison of the "sport sciences" literature across all these sports, on the other hand, is feasible and provides information on the scientific importance of the various sports.

Our analysis revealed that only nine sports (football, cycling, athletics, swimming, distance & marathon running, basketball, baseball, tennis, and rowing) represented 69% of the articles and 75% of the citations, while 11 sports (biathlon, mountain biking, archery, diving, trampoline, skateboarding, skeleton, modern pentathlon, luge, bobsleigh, and curling) accumulated a total of fewer than 50 publications.

Why a given sport attracts many publications certainly depends on a number of variables. Unsurprisingly, the sports with the most published and cited articles are very popular, and most of them are long established in the Olympic programme, e.g., from the start in 1896–1900, with the exceptions of basketball (1936) and baseball (1992). While the time since inclusion in the Olympic programme seems to be a key criterion for the attraction of scientific interest for some sports, this appears not to be the case for other, even "traditional" Olympic sports, such as wrestling or fencing (both Olympic sports since 1896). Another criterion for scientific attractiveness may be individual vs. team

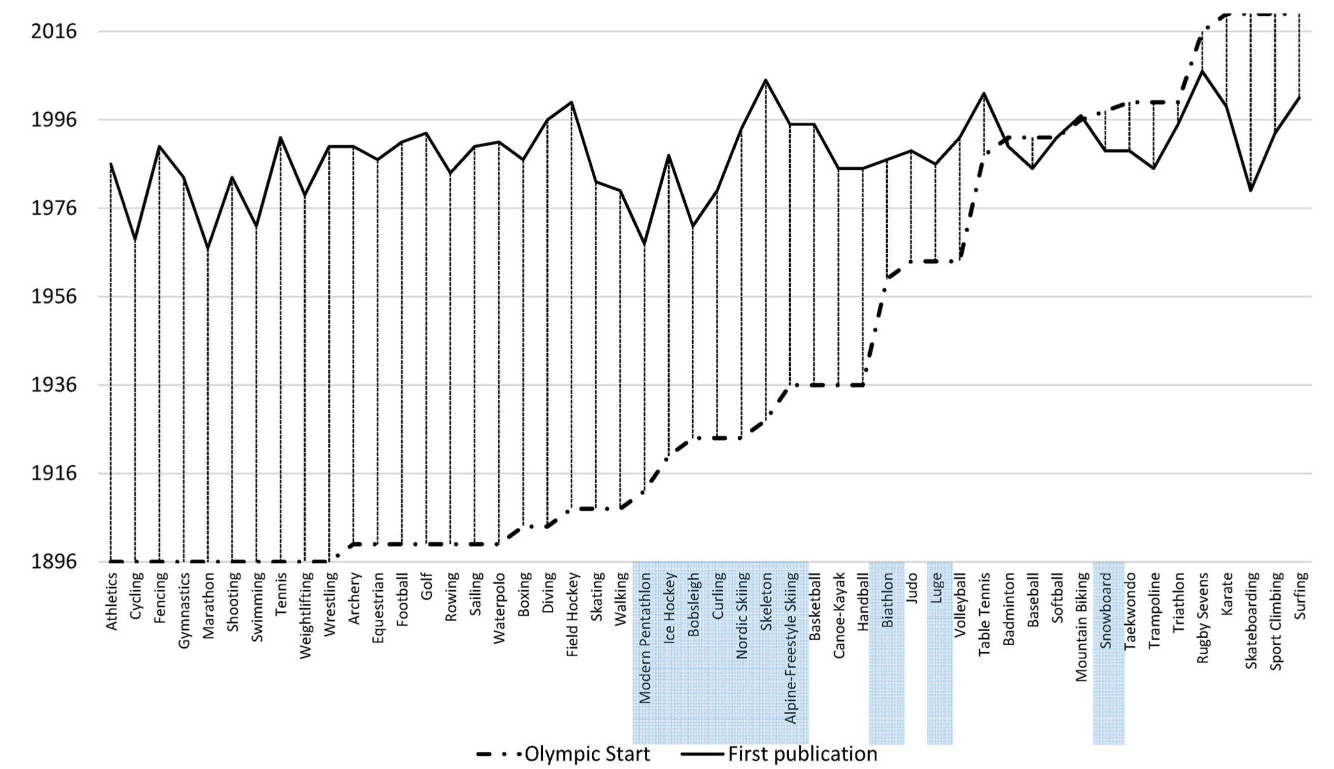

FIGURE 1 | Dates of the Olympic debut and of first publication across all summer and winter Olympic sports. Winter sports are highlighted.

sports. Team sports are highly investigated, as is confirmed by our finding that five team sports (football, basketball, volleyball, handball, and ice hockey) rank among the top 12 most cited of the 50 sports analyzed. Conversely, the impact on the scientific literature is lower in other team sports, including field hockey, water polo and rugby sevens (a recent inclusion in the Olympic programme).

When analyzing the individual sports, it is noteworthy that the sports in which performance is determined mainly by energy (aerobic and anaerobic) production—as conceptually opposed to "motor control" or "technical" sports categories—have led to a larger scientific output. Sports belonging to the first category include cycling, athletics, swimming, distance running—marathon and rowing, all of which rank among the top 10 most cited sports. Baseball (see below) and tennis are the exceptions, representing technical sports in this top 10 ranking. Supporting this notion, the technical sports golf (despite its media prominence) and gymnastics (one of the most important Olympic sports) are less frequently cited than, for example, triathlon. One may speculate that more energy-reliant sports may benefit to a greater extent from general scientific support/knowledge (i.e., exercise physiology) than the more "technical" sports (i.e., motor control). This suggestion is corroborated by the importance of the "physiology" research topic (see chapter 8 and **Figure 6**) across most sports. However, the limitation of our search to PubMed and the biomedical literature may partially account for this result.

It is very challenging to clearly appreciate why a sport attracts the interest of sport scientists. We do not exclude the possibility that this effect can be explained by more general factors (e.g., a general increase in publication numbers in recent decades). Olympic sports may be of higher scientific interest to sport scientists than non-Olympic sports. This may be related to a trend of scientific support increasingly becoming a key component of elite performance. Many scientists of excellent scientific/academic background (i.e., Dupont et al., 2005; Bangsbo et al., 2008 in football, Mountjoy et al., 2016; Mujika et al., 2019 in swimming, Mujika et al., 2019 in athletics, Jones et al., 2021 in distance running, and Hebert-Losier et al., 2017; Solli et al., 2017 in Nordic skiing, to name only a few—we apologize to many other colleagues who deserve to be on this list) are indeed servicing and advising elite athletes or teams while in parallel producing outstanding scientific research that is sometimes relevant for coaches. Until recently, the translation of "sport sciences" research to practice was often poor (Bishop, 2008), and interdependence between the practical and scientific impacts of "sport sciences" research has frequently been advocated (Coutts, 2016; Brocherie and Beard, 2020). Elite sports organizations require embedded, fast-moving, service-providing applied research scientists as well as slow-thinking researchers (Sandbakk, 2018), who, working together, will carry on producing sport-specific research.

Most elite sports institutes (e.g., Insep in France https://labos-recherche.insep.fr/fr), the IOC (https://olympics.com/

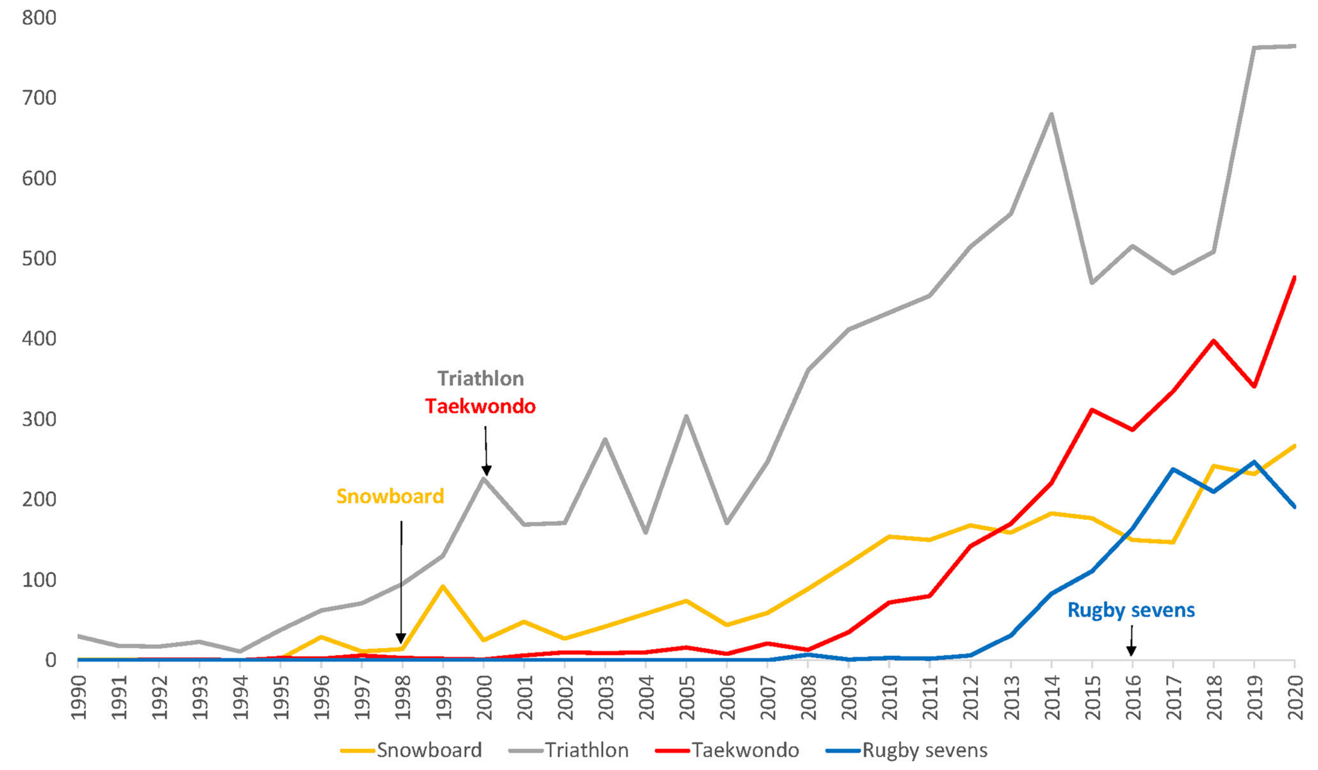

FIGURE 2 | Number of citations per year (y-axis) in four "recent" (i.e., debut at 1998 or later) Olympic sports. The date of the Olympic debut is marked by an arrow.

ioc/medical-and-scientific-commission) and some National Olympic Committees and national and international governing bodies (e.g., World Athletics https://www.worldathletics.org/about-iaaf/health-science) have developed scientific committees to stimulate research on specific topics according to their needs. Examples are programmes with the aim of implementing new rules for the protection of athletes' health by limiting concussion (Stokes et al., 2021) or heat stress (Mountjoy et al., 2012). Although the scientific support and service sector has grown tremendously in the last two decades, the impact of scientific support on sports performance remains difficult to quantify.

However, while we believe that sport-specific attractiveness is due mainly to the importance of the sport itself, it is beyond the scope of the present review to relate the present bibliometric information to other sport characteristics, such as but not limited to the number of participants, economic weight and media exposure. These points are briefly discussed in the present review but certainly also contribute to the importance of a particular sport in the scientific literature. The quality of servicing scientists at the club, federation, or sport institute levels may be a factor of influence, but the vast majority of these sports publications seem to have come from academic (i.e., employed by universities or research organizations) researchers. With the evolution of the performance support model within the professional and elite sporting environment, deemed necessary to integrate an applied research process to bridge the gap between scientists and practitioners (Brocherie and Beard, 2020), the scientific publication landscape may change in the future, even for less attractive sports.

Football (Soccer) Dominates the Scientific Literature

The dominance of football in the "sport sciences" literature is impressive. Football represents 19.7 and 26.3% of the total number of articles and citations, respectively (**Figure 3**), despite its relatively low importance with regard to Olympic medal counts (i.e., 2 of 339 gold medals at Tokyo 2020 vs. 48 in athletics, 37 in swimming and 12 in Nordic skiing or skating at Beijing 2022, to cite only the main Olympic sports). The reasons, therefore, are unrelated to the Olympics and likely are attributable to its general popularity and associated economic characteristics. Football is the most popular sport worldwide (e.g., the global audience at the FIFA World Cup 2018 was estimated to be 3.57 billion people). Half of the total revenue of the sports industry is gained by competitive sports of the spectator sports sector, amounting to approximately US$250 billion in turnover each year. The share of football accounts for an estimated 43% of this revenue and thus is much larger than the shares of other Olympic sports or even of other US professional sports; it is almost equal to the combined revenue from all US sports, including American football (13%), baseball (12%), Formula 1 auto racing (7%), basketball (6%), ice hockey (4%) and tennis (4%) (https://www.researchandmarkets.com/reports/5022446/sports-global-market-report-2020-

TABLE 4 | Top-5 articles on summer sports.

References	Articles	Number citations
1. ARCHERY		
Salazar et al. (1990)	Salazar W, Landers DM, Petruzzello SJ, Han M, Crews DJ, Kubitz KA. Hemispheric asymmetry, cardiac response, and performance in elite archers. Res Q Exerc Sport. 1990 Dec;61(4):351-9.	99
Landers et al. (1991)	Landers DM, Petruzzello SJ, Salazar W, Crews DJ, Kubitz KA, Gannon TL, et al. The influence of electrocortical biofeedback on performance in pre-elite archers. Med Sci Sports Exerc. 1991 Jan;23(1):123-9.	85
Ertan et al. (2003)	Ertan H, Kentel B, Tumer ST, Korkusuz F. Activation patterns in forearm muscles during archery shooting. Hum Mov Sci. 2003 Feb;22(1):37-45.	40
Leroyer et al. (1993)	Leroyer P, Van Hoecke J, Helal JN. Biomechanical study of the final push-pull in archery. J Sports Sci. 1993 Feb;11(1):63-9.	35
Mann and Littke (1989)	Mann DL, Littke N. Shoulder injuries in archery. Can J Sport Sci. 1989 Jun;14(2):85-92.	29
2. ATHLETICS		
Mero et al. (1992)	Mero A, Komi PV, Gregor RJ. Biomechanics of sprint running. A review. Sports Med. 1992 Jun;13(6):376-92.	363
Young et al. (1995)	Young W, McLean B, Ardagna J. Relationship between strength qualities and sprinting performance. J Sports Med Phys Fitness. 1995 Mar;35(1):13-9.	237
Hunter et al. (2005)	Hunter JP, Marshall RN, McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. J Appl Biomech. 2005 Feb;21(1):31-43.	217
Chelly and Denis (2001)	Chelly SM, Denis C. Leg power and hopping stiffness: relationship with sprint running performance. Med Sci Sports Exerc. 2001 Feb;33(2):326-33.	216
Kuitunen et al. (2002)	Kuitunen S, Komi PV, Kyrolainen H. Knee and ankle joint stiffness in sprint running. Med Sci Sports Exerc. 2002 Jan;34(1):166-73.	214
3. BADMINTON		
Cabello Manrique and Gonzalez-Badillo (2003)	Cabello Manrique D, Gonzalez-Badillo JJ. Analysis of the characteristics of competitive badminton. Br J Sports Med. 2003 Feb;37(1):62-6.	121
Phomsoupha and Laffaye (2015)	Phomsoupha M, Laffaye G. The science of badminton: game characteristics, anthropometry, physiology, visual fitness and biomechanics. Sports Med. 2015 Apr;45(4):473-95.	83
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Barrentine et al. (1998)	Barrentine SW, Fleisig GS, Whiteside JA, Escamilla RF, Andrews JR. Biomechanics of windmill softball pitching with implications about injury mechanisms at the shoulder and elbow. J Orthop Sports Phys Ther. 1998 Dec;28(6):405-15.	75
Marshall et al. (2007)	Marshall SW, Hamstra-Wright KL, Dick R, Grove KA, Agel J. Descriptive epidemiology of collegiate women's softball injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. J Athl Train. 2007 Apr-Jun;42(2):286-94.	66
Werner et al. (2006)	Werner SL, Jones DG, Guido JA, Jr., Brunet ME. Kinematics and kinetics of elite windmill softball pitching. Am J Sports Med. 2006 Apr;34(4):597-603.	62
28. SPORT CLIMBING		
Watts (2004)	Watts PB. Physiology of difficult rock climbing. Eur J Appl Physiol. 2004 Apr;91(4):361-72.	135
Mermier et al. (2000)	Mermier CM, Janot JM, Parker DL, Swan JG. Physiological and anthropometric determinants of sport climbing performance. Br J Sports Med. 2000 Oct;34(5):359-65; discussion 66.	113
Grant et al. (1996)	Grant S, Hynes V, Whittaker A, Aitchison T. Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. J Sports Sci. 1996 Aug;14(4):301-9.	107
Watts et al. (1993)	Watts PB, Martin DT, Durtschi S. Anthropometric profiles of elite male and female competitive sport rock climbers. J Sports Sci. 1993 Apr;11(2):113-7.	103
Billat et al. (1995)	Billat V, Palleja P, Charlaix T, Rizzardo P, Janel N. Energy specificity of rock climbing and aerobic capacity in competitive sport rock climbers. J Sports Med Phys Fitness. 1995 Mar;35(1):20-4.	101
29. SURFING		
Mendez-Villanueva et al. (2006)	Mendez-Villanueva A, Bishop D, Hamer P. Activity profile of world-class professional surfers during competition: a case study. J Strength Cond Res. 2006 Aug;20(3):477-82.	66
Nathanson et al. (2007)	Nathanson A, Bird S, Dao L, Tam-Sing K. Competitive surfing injuries: a prospective study of surfing-related injuries among contest surfers. Am J Sports Med. 2007 Jan;35(1):113-7.	57
Farley et al. (2012)	Farley OR, Harris NK, Kilding AE. Physiological demands of competitive surfing. J Strength Cond Res. 2012 Jul;26(7):1887-96.	57
Booth (2001)	Booth D. From bikinis to boardshorts: wahines and the paradoxes of surfing culture. J Sport Hist. 2001;28(1):3-22.	56
Furness et al. (2015)	Furness J, Hing W, Walsh J, Abbott A, Sheppard JM, Climstein M. Acute injuries in recreational and competitive surfers: incidence, severity, location, type, and mechanism. Am J Sports Med. 2015 May;43(5):1246-54.	39
30. SWIMMING		
Costill et al. (1985)	Costill DL, Kovaleski J, Porter D, Kirwan J, Fielding R, King D. Energy expenditure during front crawl swimming: predicting success in middle-distance events. Int J Sports Med. 1985 Oct;6(5):266-70.	287
Craig and Pendergast (1979)	Craig AB, Jr., Pendergast DR. Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. Med Sci Sports. 1979 Fall;11(3):278-83.	230
Costill et al. (1988)	Costill DL, Flynn MG, Kirwan JP, Houmard JA, Mitchell JB, Thomas R, et al. Effects of repeated days of intensified training on muscle glycogen and swimming performance. Med Sci Sports Exerc. 1988 Jun;20(3):249-54.	226
Gleeson et al. (1999)	Gleeson M, McDonald WA, Pyne DB, Cripps AW, Francis JL, Fricker PA, et al. Salivary IgA levels and infection risk in elite swimmers. Med Sci Sports Exerc. 1999 Jan;31(1):67-73.	223

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TABLE 4 | Continued

References	Articles	Number citations
Morgan et al. (1988)	Morgan WP, Costill DL, Flynn MG, Raglin JS, O'Connor PJ. Mood disturbance following increased training in swimmers. Med Sci Sports Exerc. 1988 Aug;20(4):408-14.	213
31. TABLE TENNIS		
Rodrigues et al. (2002)	Rodrigues ST, Vickers JN, Williams AM. Head, eye and arm coordination in table tennis. J Sports Sci. 2002 Mar;20(3):187-200.	85
Raab et al. (2005)	Raab M, Masters RS, Maxwell JP. Improving the 'how' and 'what' decisions of elite table tennis players. Hum Mov Sci. 2005 Jun;24(3):326-44.	64
Kondric et al. (2013)	Kondric M, Zagatto AM, Sekulic D. The physiological demands of table tennis: a review. J Sports Sci Med. 2013;12(3):362-70.	44
Martinent and Ferrand (2009)	Martinent G, Ferrand C. A naturalistic study of the directional interpretation process of discrete emotions during high-stakes table tennis matches. J Sport Exerc Psychol. 2009 Jun;31(3):318-36.	42
Iino and Kojima (2009)	Iino Y, Kojima T. Kinematics of table tennis topspin forehands: effects of performance level and ball spin. J Sports Sci. 2009 Oct;27(12):1311-21.	40
32. TAEKWONDO		
Bridge et al. (2014)	Bridge CA, Ferreira da Silva Santos J, Chaabene H, Pieter W, Franchini E. Physical and physiological profiles of taekwondo athletes. Sports Med. 2014 Jun;44(6):713-33.	123
Campos et al. (2012)	Campos FA, Bertuzzi R, Dourado AC, Santos VG, Franchini E. Energy demands in taekwondo athletes during combat simulation. Eur J Appl Physiol. 2012 Apr;112(4):1221-8.	109
Matsushigue et al. (2009)	Matsushigue KA, Hartmann K, Franchini E. Taekwondo: Physiological responses and match analysis. J Strength Cond Res. 2009 Jul;23(4):1112-7.	106
Kazemi et al. (2006)	Kazemi M, Waalen J, Morgan C, White AR. A profile of olympic taekwondo competitors. J Sports Sci Med. 2006; 5(CSSI):114-21.	100
Falco et al. (2009)	Falco C, Alvarez O, Castillo I, Estevan I, Martos J, Mugarra F, et al. Influence of the distance in a roundhouse kick's execution time and impact force in Taekwondo. J Biomech. 2009 Feb 9;42(3):242-8.	95
33. TENNIS		
Nirschl (1992)	Nirschl RP. Elbow tendinosis/tennis elbow. Clin Sports Med. 1992 Oct;11(4):851-70.	295
Fernandez et al. (2006)	Fernandez J, Mendez-Villanueva A, Pluim BM. Intensity of tennis match play. Br J Sports Med. 2006 May;40(5):387-91; discussion 91.	201
Ellenbecker et al. (2002)	Ellenbecker TS, Roetert EP, Bailie DS, Davies GJ, Brown SW. Glenohumeral joint total rotation range of motion in elite tennis players and baseball pitchers. Med Sci Sports Exerc. 2002 Dec;34(12):2052-6.	188
O' Donoghue and Ingram (2001)	O' Donoghue P, Ingram B. A notational analysis of elite tennis strategy. J Sports Sci. 2001 Feb;19(2):107-15.	179
Mishra et al. (2014)	Mishra AK, Skrepnik NV, Edwards SG, Jones GL, Sampson S, Vermillion DA, et al. Efficacy of platelet-rich plasma for chronic tennis elbow: a double-blind, prospective, multicenter, randomized controlled trial of 230 patients. Am J Sports Med. 2014 Feb;42(2):463-71.	179
34. TRAMPOLINE		
Eliasson et al. (2002)	Eliasson K, Larsson T, Mattsson E. Prevalence of stress incontinence in nulliparous elite trampolinists. Scand J Med Sci Sports. 2002 Apr;12(2):106-10.	99
Nysted and Drogset (2006)	Nysted M, Drogset JO. Trampoline injuries. Br J Sports Med. 2006 Dec;40(12):984-7.	42
Da Roza et al. (2015)	Da Roza T, Brandao S, Mascarenhas T, Jorge RN, Duarte JA. Volume of training and the ranking level are associated with the leakage of urine in young female trampolinists. Clin J Sport Med. 2015 May;25(3):270-5.	34
Blajer and Czaplicki (2001)	Blajer W, Czaplicki A. Modeling and inverse simulation of somersaults on the trampoline. J Biomech. 2001 Dec;34(12):1619-29.	31
Hume et al. (1996)	Hume PA, Chalmers DJ, Wilson BD. Trampoline injury in New Zealand: emergency care. Br J Sports Med. 1996 Dec;30(4):327-30.	30
35. TRIATHLON		
Jeukendrup (2011)	Jeukendrup AE. Nutrition for endurance sports: marathon, triathlon, and road cycling. J Sports Sci. 2011;29 Suppl 1:S91-9.	168
Plews et al. (2012)	Plews DJ, Laursen PB, Kilding AE, Buchheit M. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. Eur J Appl Physiol. 2012 Nov;112(11):3729-41.	139
Coutts et al. (2007)	Coutts AJ, Wallace LK, Slattery KM. Monitoring changes in performance, physiology, biochemistry, and psychology during overreaching and recovery in triathletes. Int J Sports Med. 2007 Feb;28(2):125-34.	139
Millet et al. (2009)	Millet GP, Vleck VE, Bentley DJ. Physiological differences between cycling and running: lessons from triathletes. Sports Med. 2009;39(3):179-206.	128
Bentley et al. (2002)	Bentley DJ, Millet GP, Vleck VE, McNaughton LR. Specific aspects of contemporary triathlon: implications for physiological analysis and performance. Sports Med. 2002;32(6):345-59.	109

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TABLE 4 | Continued

References	Articles	Number citations
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Newton et al. (1999)	Newton RU, Kraemer WJ, Hakkinen K. Effects of ballistic training on preseason preparation of elite volleyball players. Med Sci Sports Exerc. 1999 Feb;31(2):323-30.	221
Ferretti et al. (1992)	Ferretti A, Papandrea P, Conteduca F, Mariani PP. Knee ligament injuries in volleyball players. Am J Sports Med. 1992 Mar-Apr;20(2):203-7.	208
Bahr and Bahr (1997)	Bahr R, Bahr IA. Incidence of acute volleyball injuries: a prospective cohort study of injury mechanisms and risk factors. Scand J Med Sci Sports. 1997 Jun;7(3):166-71.	206
Bahr et al. (1997)	Bahr R, Lian O, Bahr IA. A twofold reduction in the incidence of acute ankle sprains in volleyball after the introduction of an injury prevention program: a prospective cohort study. Scand J Med Sci Sports. 1997 Jun;7(3):172-7.	179
Verhagen et al. (2004)	Verhagen EA, Van der Beek AJ, Bouter LM, Bahr RM, Van Mechelen W. A one season prospective cohort study of volleyball injuries. Br J Sports Med. 2004 Aug;38(4):477-81.	178
37. WALKING		
Bassett et al. (2008)	Bassett DR, Jr., Pucher J, Buehler R, Thompson DL, Crouter SE. Walking, cycling, and obesity rates in Europe, North America, and Australia. J Phys Act Health. 2008 Nov;5(6):795-814.	362
Heller et al. (2001)	Heller MO, Bergmann G, Deuretzbacher G, Durselen L, Pohl M, Claes L, et al. Musculo-skeletal loading conditions at the hip during walking and stair climbing. J Biomech. 2001 Jul;34(7):883-93.	316
Ryan et al. (2006)	Ryan CG, Grant PM, Tigbe WW, Granat MH. The validity and reliability of a novel activity monitor as a measure of walking. Br J Sports Med. 2006 Sep;40(9):779-84.	272
Lee and Buchner (2008)	Lee IM, Buchner DM. The importance of walking to public health. Med Sci Sports Exerc. 2008 Jul;40(7 Suppl):S512-8.	254
Kelly et al. (2014)	Kelly P, Kahlmeier S, Gotschi T, Orsini N, Richards J, Roberts N, et al. Systematic review and meta-analysis of reduction in all-cause mortality from walking and cycling and shape of dose response relationship. Int J Behav Nutr Phys Act. 2014 Oct 24;11:132.	224
38. WATERPOLO		
Royal et al. (2006)	Royal KA, Farrow D, Mujika I, Halson SL, Pyne D, Abernethy B. The effects of fatigue on decision making and shooting skill performance in water polo players. J Sports Sci. 2006 Aug;24(8):807-15.	140
Smith (1998)	Smith HK. Applied physiology of water polo. Sports Med. 1998 Nov;26(5):317-34.	124
McMaster et al. (1991)	McMaster WC, Long SC, Caiozzo VJ. Isokinetic torque imbalances in the rotator cuff of the elite water polo player. Am J Sports Med. 1991 Jan-Feb;19(1):72-5.	107
Lupo et al. (2010)	Lupo C, Tessitore A, Minganti C, Capranica L. Notational analysis of elite and sub-elite water polo matches. J Strength Cond Res. 2010 Jan;24(1):223-9.	75
Tsekouras et al. (2005)	Tsekouras YE, Kavouras SA, Campagna A, Kotsis YP, Syntosi SS, Papazoglou K, et al. The anthropometrical and physiological characteristics of elite water polo players. Eur J Appl Physiol. 2005 Sep;95(1):35-41.	73
39. WEIGHTLIFTING		
Tricoli et al. (2005)	Tricoli V, Lamas L, Carnevale R, Ugrinowitsch C. Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs. J Strength Cond Res. 2005 May;19(2):433-7.	169
Haff et al. (2005)	Haff GG, Carlock JM, Hartman MJ, Kilgore JL, Kawamori N, Jackson JR, et al. Force-time curve characteristics of dynamic and isometric muscle actions of elite women olympic weightlifters. J Strength Cond Res. 2005 Nov;19(4):741-8.	119
Hori et al. (2008)	Hori N, Newton RU, Andrews WA, Kawamori N, McGuigan MR, Nosaka K. Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction? J Strength Cond Res. 2008 Mar;22(2):412-8.	115
Pearson et al. (2002)	Pearson SJ, Young A, Macaluso A, Devito G, Nimmo MA, Cobbold M, et al. Muscle function in elite master weightlifters. Med Sci Sports Exerc. 2002 Jul;34(7):1199-206.	113
Garhammer, 1980)	Garhammer J. Power production by Olympic weightlifters. Med Sci Sports Exerc. 1980 Spring;12(1):54-60.	111
40. WRESTLING		
Gould et al. (1993b)	Gould D, Eklund RC, Jackson SA. Coping strategies used by U.S. Olympic wrestlers. Res Q Exerc Sport. 1993 Mar;64(1):83-93.	203
Steen and Brownell (1990)	Steen SN, Brownell KD. Patterns of weight loss and regain in wrestlers: has the tradition changed? Med Sci Sports Exerc. 1990 Dec;22(6):762-8.	176
Kraemer et al. (2001)	Kraemer WJ, Fry AC, Rubin MR, Triplett-McBride T, Gordon SE, Koziris LP, et al. Physiological and performance responses to tournament wrestling. Med Sci Sports Exerc. 2001 Aug;33(8):1367-78.	168
Oppliger et al. (1996)	Oppliger RA, Case HS, Horswill CA, Landry GL, Shelter AC. American College of Sports Medicine position stand. Weight loss in wrestlers. Med Sci Sports Exerc. 1996 Jun;28(6):ix-xii.	141
Webster et al. (1990)	Webster S, Rutt R, Weltman A. Physiological effects of a weight loss regimen practiced by college wrestlers. Med Sci Sports Exerc. 1990 Apr;22(2):229-34.	135

TABLE 5 | Top-5 articles on winter sports.

References	Articles	Number citations
1. ALPINE SKIING		
Ettlinger et al. (1995)	Ettlinger CF, Johnson RJ, Shealy JE. A method to help reduce the risk of serious knee sprains incurred in alpine skiing. Am J Sports Med. 1995 Sep-Oct;23(5):531-7.	173
Florenes et al. (2009)	Florenes TW, Bere T, Nordsletten L, Heir S, Bahr R. Injuries among male and female World Cup alpine skiers. Br J Sports Med. 2009 Dec;43(13):973-8.	104
Burtscher et al. (2008)	Burtscher M, Gatterer H, Flatz M, Sommersacher R, Woldrich T, Ruedl G, et al. Effects of modern ski equipment on the overall injury rate and the pattern of injury location in Alpine skiing. Clin J Sport Med. 2008 Jul;18(4):355-7.	95
Bere et al. (2011)	Bere T, Florenes TW, Krosshaug T, Koga H, Nordsletten L, Irving C, et al. Mechanisms of anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. Am J Sports Med. 2011 Jul;39(7):1421-9.	90
Pujol et al. (2007)	Pujol N, Blanchi MP, Chambat P. The incidence of anterior cruciate ligament injuries among competitive Alpine skiers: a 25-year investigation. Am J Sports Med. 2007 Jul;35(7):1070-4.	89
2. BIATHLON		
Vickers and Williams (2007)	1. Vickers JN, Williams AM. Performing under pressure: the effects of physiological arousal, cognitive anxiety, and gaze control in biathlon. J Mot Behav. 2007 Sep;39(5):381-94.	160
Heinicke et al. (2005)	1. Heinicke K, Heinicke I, Schmidt W, Wolfarth B. A three-week traditional altitude training increases hemoglobin mass and red cell volume in elite biathlon athletes. Int J Sports Med. 2005 Jun;26(5):350-5.	81
Hoffman et al. (1992)	1. Hoffman MD, Gilson PM, Westenburg TM, Spencer WA. Biathlon shooting performance after exercise of different intensities. Int J Sports Med. 1992 Apr;13(3):270-3.	64
Rundell and Bacharach (1995)	1. Rundell KW, Bacharach DW. Physiological characteristics and performance of top U.S. biathletes. Med Sci Sports Exerc. 1995 Sep;27(9):1302-10.	38
Rundell (1995)	1. Rundell KW. Treadmill roller ski test predicts biathlon roller ski race results of elite U.S. biathlon women. Med Sci Sports Exerc. 1995 Dec;27(12):1677-85.	35
3. BOBSLEIGH		
Dabnichki and Avital (2006)	Dabnichki P, Avital E. Influence of the postion of crew members on aerodynamics performance of two-man bobsleigh. J Biomech. 2006;39(15):2733-42.	29
Haralambie et al. (1976)	Haralambie G, Cerny FJ, Huber G. Serum enzyme levels after bobsled racing. J Sports Med Phys Fitness. 1976 Mar;16(1):54-6.	11
Reid (2003)	Reid SA. Stress fracture of the ulna in an elite bobsled brakeman. Clin J Sport Med. 2003 Sep;13(5):306-8.	4
Lopes and Alouche (2016)	Lopes AD, Alouche SR. Two-Man Bobsled Push Start Analysis. J Hum Kinet. 2016 Apr 1;50:63-70.	4
Okada et al. (1972)	Okada A, Miyake H, Takizawa A, Minami M. A study on the excreted catecholamines in the urine of Bobsleigh-tobogganing contestants. J Sports Med Phys Fitness. 1972 Jun;12(2):71-5.	3
4. CURLING		
Bradley (2009)	Bradley JL. The sports science of curling: a practical review. J Sports Sci Med. 2009;8(4):495-500.	13
Robertson et al. (2017)	Reeser JC, Berg RL. Self-reported injury patterns among competitive curlers in the United States: a preliminary investigation into the epidemiology of curling injuries. Br J Sports Med. 2004 Oct;38(5):E29.	5
Berry et al. (2013)	Berry JW, Romanick MA, Koerber SM. Injury type and incidence among elite level curlers during world championship competition. Res Sports Med. 2013;21(2):159-63.	4
Stone et al. (2018)	Stone RC, Rakhamilova Z, Gage WH, Baker J. Curling for Confidence: Psychophysical Benefits of Curling for Older Adults. J Aging Phys Act. 2018 Apr 1;26(2):267-75.	2
Pojskic et al. (2020)	Pojskic H, McGawley K, Gustafsson A, Behm DG. The Reliability and Validity of a Novel Sport-Specific Balance Test to Differentiate Performance Levels in Elite Curling Players. J Sports Sci Med. 2020 Jun;19(2):337-46.	1
5. ICE HOCKEY		
Philippon et al. (2010)	Philippon MJ, Weiss DR, Kuppersmith DA, Briggs KK, Hay CJ. Arthroscopic labral repair and treatment of femoroacetabular impingement in professional hockey players. Am J Sports Med. 2010 Jan;38(1):99-104.	207
Tyler et al. (2001)	Tyler TF, Nicholas SJ, Campbell RJ, McHugh MP. The association of hip strength and flexibility with the incidence of adductor muscle strains in professional ice hockey players. Am J Sports Med. 2001 Mar-Apr;29(2):124-8.	205
Sherar et al. (2007)	Sherar LB, Baxter-Jones AD, Faulkner RA, Russell KW. Do physical maturity and birth date predict talent in male youth ice hockey players? J Sports Sci. 2007 Jun;25(8):879-86.	195
Williamson and Goodman (2006)	Williamson IJ, Goodman D. Converging evidence for the under-reporting of concussions in youth ice hockey. Br J Sports Med. 2006 Feb;40(2):128-32; discussion−32.	189
Flik et al. (2005)	Flik K, Lyman S, Marx RG. American collegiate men's ice hockey: an analysis of injuries. Am J Sports Med. 2005 Feb;33(2):183-7.	165

(Continued)

TABLE 5 | Continued

References	Articles	Number citations
6. LUGE		
Platzer et al. (2009)	Platzer HP, Raschner C, Patterson C. Performance-determining physiological factors in the luge start. J Sports Sci. 2009 Feb 1;27(3):221-6.	20
Cummings et al. (1997)	Cummings RS, Jr., Shurland AT, Prodoehl JA, Moody K, Sherk HH. Injuries in the sport of luge. Epidemiology and analysis. Am J Sports Med. 1997 Jul-Aug;25(4):508-13.	17
Crossland et al. (2011)	Crossland BW, Hartman JE, Kilgore JL, Hartman MJ, Kaus JM. Upper-body anthropometric and strength measures and their relationship to start time in elite luge athletes. J Strength Cond Res. 2011 Oct;25(10):2639-44.	10
Mossner et al. (2011)	Mossner M, Hasler M, Schindelwig K, Kaps P, Nachbauer W. An approximate simulation model for initial luge track design. J Biomech. 2011 Mar 15;44(5):892-6.	6
Lembert et al. (2011)	Lembert S, Schachner O, Raschner C. Development of a measurement and feedback training tool for the arm strokes of high-performance luge athletes. J Sports Sci. 2011 Dec;29(15):1593-601.	4
7. NORDIC SKIING		
Millet and Lepers (2004)	Millet GY, Lepers R. Alterations of neuromuscular function after prolonged running, cycling and skiing exercises. Sports Med. 2004;34(2):105-16.	239
Holmberg et al. (2005)	Holmberg HC, Lindinger S, Stoggl T, Eitzlmair E, Muller E. Biomechanical analysis of double poling in elite cross-country skiers. Med Sci Sports Exerc. 2005 May;37(5):807-18.	177
Hoff et al. (1999)	Hoff J, Helgerud J, Wisloff U. Maximal strength training improves work economy in trained female cross-country skiers. Med Sci Sports Exerc. 1999 Jun;31(6):870-7.	121
Grimsmo et al. (2010)	Grimsmo J, Grundvold I, Maehlum S, Arnesen H. High prevalence of atrial fibrillation in long-term endurance cross-country skiers: echocardiographic findings and possible predictors–a 28-30 years follow-up study. Eur J Cardiovasc Prev Rehabil. 2010 Feb;17(1):100-5.	118
Andersson et al. (2010)	Andersson E, Supej M, Sandbakk O, Sperlich B, Stoggl T, Holmberg HC. Analysis of sprint cross-country skiing using a differential global navigation satellite system. Eur J Appl Physiol. 2010 Oct;110(3):585-95.	87
8. SKATING		
Gould et al. (1993a)	Gould D, Finch LM, Jackson SA. Coping strategies used by national champion figure skaters. Res Q Exerc Sport. 1993 Dec;64(4):453-68.	142
Herzog et al. (1991)	Herzog W, Guimaraes AC, Anton MG, Carter-Erdman KA. Moment-length relations of rectus femoris muscles of speed skaters/cyclists and runners. Med Sci Sports Exerc. 1991 Nov;23(11):1289-96.	121
van Ingen Schenau et al. (1994)	van Ingen Schenau GJ, de Koning JJ, de Groot G. Optimisation of sprinting performance in running, cycling and speed skating. Sports Med. 1994 Apr;17(4):259-75.	90
van Ingen Schenau (1982)	van Ingen Schenau GJ. The influence of air friction in speed skating. J Biomech. 1982;15(6):449-58.	90
Foster et al. (1999)	Foster C, Rundell KW, Snyder AC, Stray-Gundersen J, Kemkers G, Thometz N, et al. Evidence for restricted muscle blood flow during speed skating. Med Sci Sports Exerc. 1999 Oct;31(10):1433-40.	70
9. SKELETON		
Bullock et al. (2008)	Bullock N, Martin DT, Ross A, Rosemond CD, Jordan MJ, Marino FE. Acute effect of whole-body vibration on sprint and jumping performance in elite skeleton athletes. J Strength Cond Res. 2008 Jul;22(4):1371-4.	55
Bullock et al. (2009)	Bullock N, Gulbin JP, Martin DT, Ross A, Holland T, Marino F. Talent identification and deliberate programming in skeleton: ice novice to Winter Olympian in 14 months. J Sports Sci. 2009 Feb 15;27(4):397-404.	51
Sands et al. (2005)	Sands WA, Smith LS, Kivi DM, McNeal JR, Dorman JC, Stone MH, et al. Anthropometric and physical abilities profiles: US National Skeleton Team. Sports Biomech. 2005 Jul;4(2):197-214.	31
Zanoletti et al. (2006)	Zanoletti C, La Torre A, Merati G, Rampinini E, Impellizzeri FM. Relationship between push phase and final race time in skeleton performance. J Strength Cond Res. 2006 Aug;20(3):579-83.	26
Bullock et al. (2007)	Bullock N, Martin DT, Ross A, Rosemond D, Marino FE. Effect of long haul travel on maximal sprint performance and diurnal variations in elite skeleton athletes. Br J Sports Med. 2007 Sep;41(9):569-73; discussion 73.	25
10. SNOWBOARD		
Bladin et al. (1993)	Bladin C, Giddings P, Robinson M. Australian snowboard injury data base study. A four-year prospective study. Am J Sports Med. 1993 Sep-Oct;21(5):701-4.	109
Kim et al. (2012)	Kim S, Endres NK, Johnson RJ, Ettlinger CF, Shealy JE. Snowboarding injuries: trends over time and comparisons with alpine skiing injuries. Am J Sports Med. 2012 Apr;40(4):770-6.	86
Pino and Colville (1989)	Pino EC, Colville MR. Snowboard injuries. Am J Sports Med. 1989 Nov-Dec;17(6):778-81.	85
Tarazi et al. (1999)	Tarazi F, Dvorak MF, Wing PC. Spinal injuries in skiers and snowboarders. Am J Sports Med. 1999 Mar-Apr;27(2):177-80.	83
Ronning et al. (2001)	Ronning R, Ronning I, Gerner T, Engebretsen L. The efficacy of wrist protectors in preventing snowboarding injuries. Am J Sports Med. 2001 Sep-Oct;29(5):581-5.	77

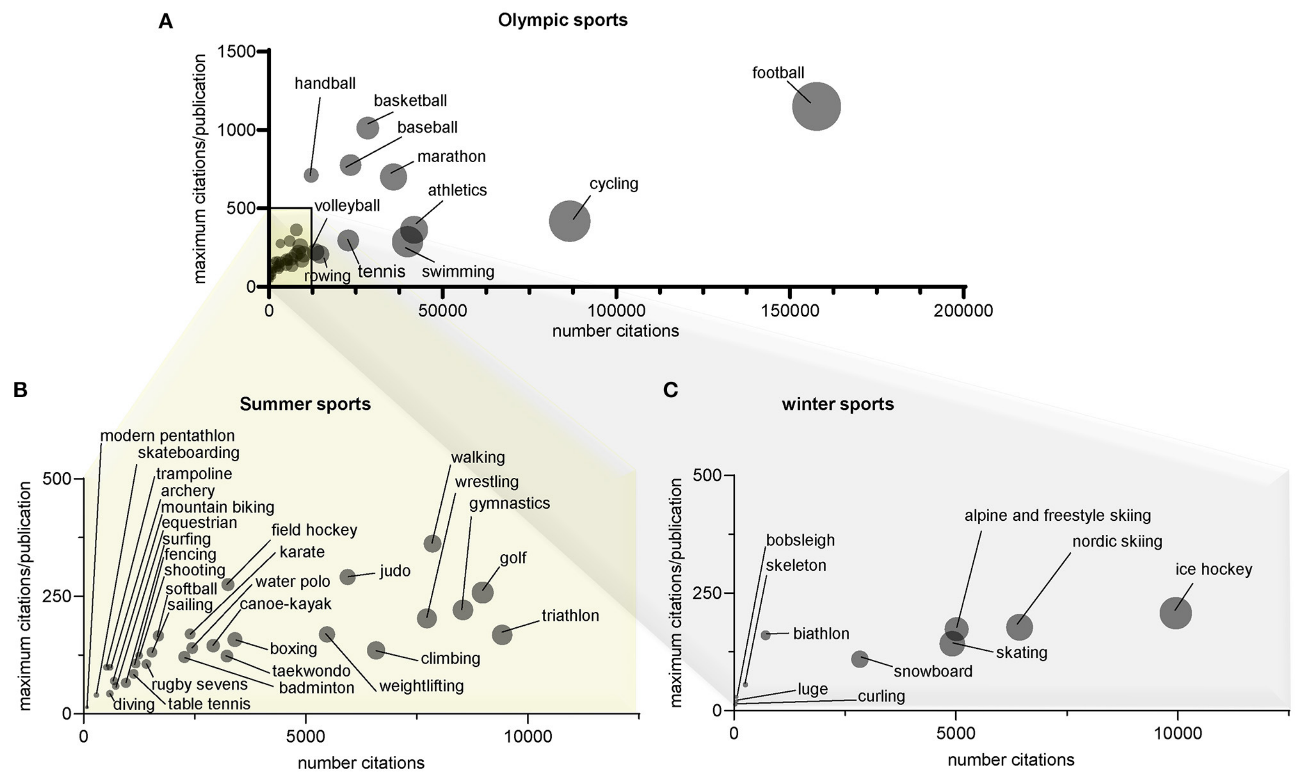

FIGURE 3 | Publication and citation numbers across all Olympic sports. All Olympic sports are depicted in panel **(A)**. Zooms of sports with citation ranges from 0 to 12,500 citations and maximum citations/publication of 500 are provided in **(B)** for summer and **(C)** for winter Olympic sports. Bubble sizes reflect numbers of publications for each sport relative to the greatest bubble of each panel. Highest publication numbers: **(A)** football—4,937, **(B)** golf—491, and **(C)** ice-hockey—540.

30-covid-19). While our findings are in line with previous results (Brito et al., 2018), the consequences and implications of the scientific dominance of football remain unclear. It is tempting to relate such scientific proliferation to the already well-organized performance support services within professional and elite football (Brocherie and Beard, 2020). However, to our knowledge, there has been no comprehensive analysis of the number of scientists working in professional football, even if it is obvious that this segment has grown considerably in the last decade, especially in the clubs of the five major football leagues in Europe (i.e., England, Spain, Germany, Italy, and France). This may have provided an edge over many other sports that are still in the process of establishing efficient structures (e.g., some leading US sports league franchises) (Brocherie and Beard, 2020).

Importance of Team Sports, Particularly American Professional Sports

Several North American professional sports are highly ranked in terms of bibliometrics. As for football, it is likely that the economic characteristics of the main North American national leagues (Major League Baseball, National Basketball Association, and National Hockey League (estimated at 5.5, 4.6, and 2.2 billion US dollars in 2015, respectively; https://www.ameriresearch.com/global-football-sports-market/) may be one reason for the scientific interest in these sports. Moreover, "sport sciences" is a well-established academic discipline, and the USA is a leading contributor in this field, as is exemplified by the largest "sport sciences" society worldwide, *American College of Sports Medicine* (ACSM) (www.acsm.org), with more than 50,000 members and certified professionals from 90 countries around the globe.

In line with other team sports (e.g., volleyball, handball, and field hockey), publications related to injuries (prevention and rehabilitation) are relatively more important in team sports (>20% of the total sport-specific articles; **Figure 6**) than in the main individual sports (cycling, athletics, swimming, distance running—marathon, etc.). This may stem from a higher degree of professionalization and therefore specialization of permanent full-time medical staff in team sports due to the economic power of these sports and the financial value of professional players.

Winter Sports Generate Minor Scientific Production

Despite some parts of the world being particularly passionate about winter sports (e.g., Sweden and Norway for Nordic skiing, Russia and Canada for ice hockey, and Austria and Switzerland for alpine skiing), the audience for winter sports and number of participants remain comparatively low worldwide. This is likely due primarily to geographical and climatic limitations (i.e., especially the lack of snow) for the development of winter

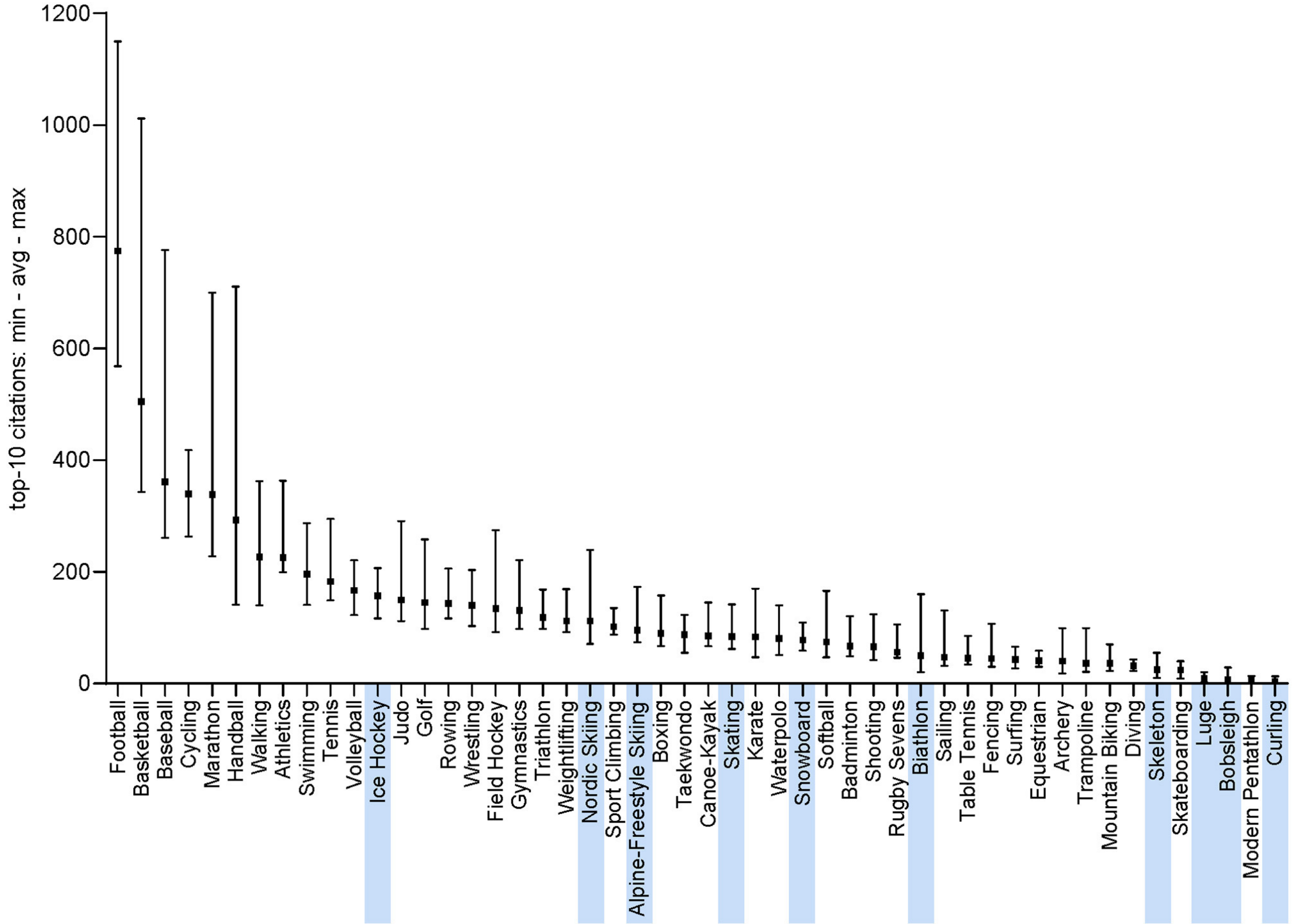

FIGURE 4 | Maximum (upper boundary), average (square) and minimum (lower boundary) numbers of citations of the top-10 publications of each sport. Winter sports are highlighted.

sports. The lower importance of winter sports becomes clear when comparing the latest summer and winter Olympic games. A record number of 2,922 athletes from 92 countries participated in the Pyeongchang 2018 Winter Games, while 11,362 athletes from 204 countries participated in the Rio de Janeiro 2016 Summer Games. A similar discrepancy is observed with regard to the number of sports and disciplines, with 102 events in 7 sports (and 15 disciplines) at the 2018 winter Olympic games vs. 306 events in 28 sports and 43 disciplines at the 2016 summer games.

In the European Nordic countries, sport sciences have a long tradition of excellence, owing primarily to the work of famous pioneers in exercise physiology (e.g., Saltin and Astrand, 1967) who performed early studies, including some on Nordic skiers. This might partly explain why Nordic skiing is the second most cited winter sport (after ice hockey—see above).

Most Articles are Published in a Limited Number of Journals

Six journals of 116 included in our search (*J Strength Cond Res*, 10.0%; *J Sports Sci*, 7.7%; *J Sports Med Phys Fitness*, 6.2%; *Br J Sports Med*, 5.5%; *Int J Sports Med*, 5.3%; and *Med Sci Sports Exerc*, 5.2%) contained 40% of all analyzed publications. These leading journals publish articles predominantly on applied research as well as on conditioning or training and testing (e.g., *J Strength Cond Res*, *J Sports Med Phys Fitness,* and *J Sports Sci)*. Some are tightly connected to powerful organizations (e.g., *Br J Sports Med*, which regularly publishes reports or statements of the IOC, or *Med Sci Sports Exerc*, which belongs to the ACSM).

Our search included 116 journals, but many of them do not publish "biomedical" articles (accessible in PubMed) specific to any of the Olympic sports. The scope of some journals is very broad (e.g., applied physiology in *J Appl Physiol*) or very narrow (e.g., *High Alt Med Biol*); articles focusing on one given sport in those journals are thus less frequent. Many journals are furthermore relatively new in PubMed (e.g., *Int J Sports Physiol Perf* and *Front Sports Active Living*). Finally, the fact that most articles are published in only a few journals may render questionable the profusion of (too?) many journals in the "sport sciences" field, which has been growing since the early 2000's.

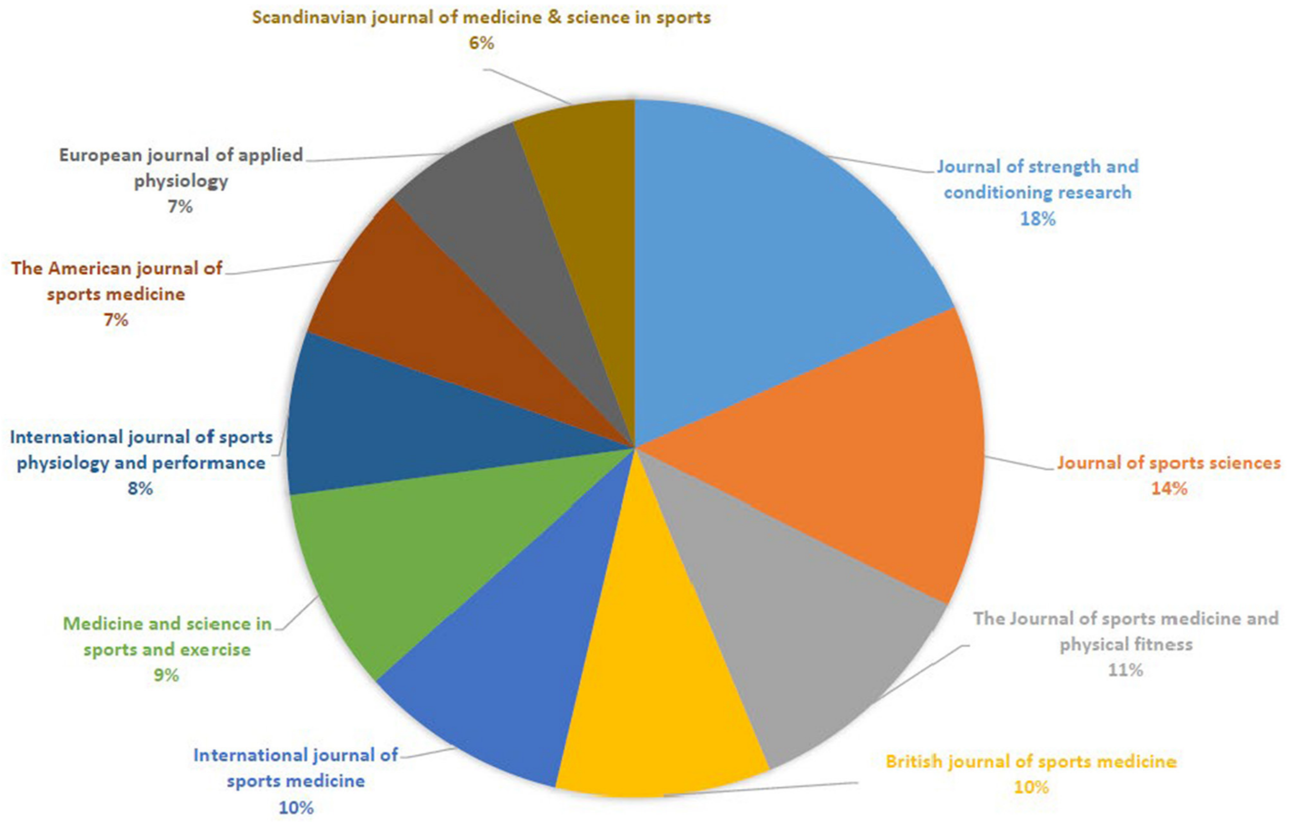

FIGURE 5 | Distribution of major "Olympic sports science" publications across journals for all Olympic sports.

The Entry of a Sport Into the Olympic Programme Translates Into an Increase in Scientific Publications

We scrutinized whether the Olympic entrance of the "recent" Olympic sports (e.g., inserted in the Olympic programme in the last 25 years: snowboard in 1998; trampoline, triathlon, and taekwondo in 2000; rugby sevens in 2016; and surfing, karate, sport climbing, and skateboarding in 2020), might have impacted their specific scientific attractiveness. **Figure 2** shows the evolution of yearly citation numbers between 1990 and 2020 with the date of the entrance into the Olympic programme for four "recent" sports (snowboard, triathlon taekwondo, and rugby sevens). Whether entrance into the programme has a positive effect remains unclear, even if an increase in the publication rate is observable 6–8 years after (for snowboard and taekwondo) or several years before (as is clearly shown for rugby sevens and triathlon) nomination as an Olympic sport. Overall, the "Olympic legacy" does not seem to stimulate a large increase in the volume of articles or citations (Thomas et al., 2016).

Of these "recent" Olympic sports, triathlon is by far the most productive of scientific output (**Figure 2**). As discussed in chapter 1, this may stem from the nature of the sport, which is highly energetic and of interest to physiologists, while other "recent" sports are less aerobic.

Local/Cultural Influence and/or Influence of Editorial Board Composition

Sports carry strong cultural and political meanings for their practitioners and spectators and powerfully symbolize identities and communities (Millet and Giulianotti, 2019). It is therefore not surprising—and in a sense reassuring in our globalized world—to find that a local sporting culture can impact the scientific output, as is testified by the overrepresentation of alpine and Nordic skiing in *Scand J Med Sci Sport*. "Sport sciences" (like most other scientific fields) are dominated by Anglo-Saxon countries (especially the USA, UK, Australia, and Canada). As has recently been observed (Pyne, 2021), research in several of the world's leading sporting nations (e.g., Russia, China, Japan, and South Korea; all top 8 nations at the 2016 Summer Olympic Games) is underrepresented in "sport sciences" journals that are published mostly in English. It is beyond the scope of this review to analyze all the other potential factors or barriers (economic, political, religious, gender based, etc.) that bias the over- vs. under-representation of a given sport in the "sport sciences" literature, but more cultural, geographical and gender diversity is needed. Another observation is the influence of the composition of the editorial boards of the journals on editorial policy as well as the published content. All the above-mentioned factors influence regular publications on certain sports in journals, such as rugby sevens in *Int J Sports Physiol Perf or* tennis in *Br J*

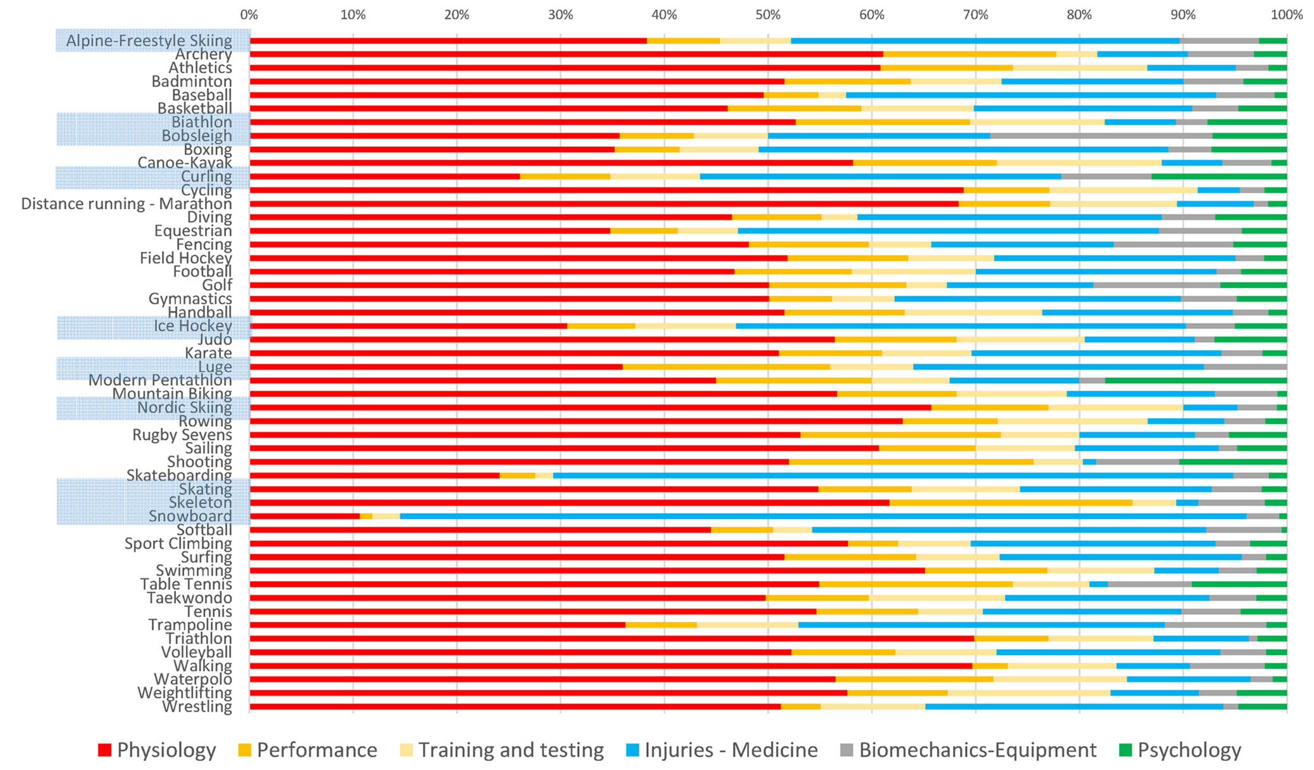

FIGURE 6 | Distribution of publications between six research topics across all summer and winter Olympic sports. Winter sports are highlighted.

Sports Med, while some sports that are extremely popular in Asia (taekwondo and table tennis) lack comparable platforms for scientific exchange.

Relative Distribution of Six Main Research Topics Across Sports

We analyzed the relative distribution of six research topics (i.e., physiology, performance, training and testing, injuries and medicine, biomechanics, and psychology) across all summer and winter Olympic sports publications since the analysis may provide informational particularities that are especially relevant for research on these sports or on the determinants of performance, which vary considerably among sports. For example, it has long been known that maximal aerobic power is paramount in cross-country skiing, cycling, distance running and rowing, as is evidenced by the high maximal oxygen consumption (VO_{2max}) values in top performers in these sports (Haugen et al., 2018), who reach VO_{2max} values of >90 ml/kg/min (Millet and Jornet, 2019). Although "physiology" covers other aspects than aerobic capacity, many publications (approximately two-thirds) on sports such as triathlon, swimming, and walking concern physiological aspects due to these sports' high reliance on aerobic capacities.

Whereas, the scientific literature on many sports is dominated by physiological topics, research on other sports focuses on associated injuries-illnesses. The topic "injuries and medicine" is paramount (i.e., > 40% of related publications) in five summer (baseball, boxing, equestrian, skateboarding, and softball) and 4 winter (alpine freestyle skiing, curling, ice hockey, and snowboarding) sports. Of the publications, 65% of those on skateboarding and 82% of those on snowboarding concern injuries. Deeper analyses of these publications are required to differentiate the types and causes of injuries between contact sports (e.g., boxing and ice hockey), sports inducing falls (equestrian, alpine skiing, snowboarding, and skateboarding), and sports inducing overuse injuries (e.g., elbow injury in baseball and softball). The "injuries and illnesses prevention and incidence" topic is of the highest priority in elite sports; the IOC medical and scientific commission (https://olympics.com/ioc/medical-and-scientific-commission) publishes regular reports on injuries and illness incidences in the summer (Soligard et al., 2017) and winter (Soligard et al., 2019) Olympic games. During the last summer games in Rio de Janeiro in 2016, the injury incidence ranged from 38% in BMX cycling to 0–3% in canoeing, rowing, shooting, archery, swimming, golf, and table tennis, while the illness incidence was 10–12% in diving, swimming, sailing, canoeing-kayaking and equestrian (Soligard et al., 2017). During the last winter games in Pyeongchang in 2018, the injury incidence was highest (20–28%) in freestyle skiing and snowboarding and lowest (2–6%) in Nordic combined, biathlon, snowboard slalom, moguls, and cross-country skiing. The illness incidences ranged between 13 and 15% in biathlon, curling, bobsleigh, and snowboard slalom (Soligard et al., 2019).

Surprisingly, in every sport, the number of publications on psychology-related topics is quite low. Only for curling, shooting, and modern pentathlon are >10% of the sport-specific publications related to psychology, followed by table tennis. All these sports require extreme accuracy and self-control. The possibility that this low representation of psychological articles relates to the applied methodology (e.g., the database searched was PubMed) cannot be excluded, but most of the leading sport psychology journals (e.g., *Journal of Sport & Exercise Psychology*) were included in our search. These findings thus could also indicate that sport psychology is less represented than other scientific areas (physiology, medicine) in the literature. The potential underrepresentation of sport psychology should encourage sport psychologists or mental coaches to publish more of their research since there is no doubt that mental skills are an important aspect of performance in all sports.

STRENGTH AND LIMITATIONS

The main strength of this review is the exhaustive bibliometric analysis and review across all Olympic sports. To our knowledge, no similar work is available to date. The volume of extracted articles, the clear delimitation of journals and sports and the subsequent analysis permitted us to extract information on how the "sport sciences" field is structured and organized to characterize the research body on Olympic sports and highlight sports-related differential peculiarities, developments and limitations of the scientific literature.

Some limitations must be acknowledged. First, the search was performed only in the titles of the articles and did not include searching abstracts, keywords or text. Since our aim was to compare the literature on individual sports, this method may be better suited to extracting articles related primarily to one sport without risking the inclusion of false positives that refer to specific sports only marginally or incidentally. Not all physiology or medical articles on "athletes" were included since these articles can also refer to non-specific physiological responses or mechanisms. Instead, we targeted each sport or the athletes of that sport and applied clear exclusion criteria to enhance the specificity of the search strategy. However, minor categorization inaccuracies due to the high volume of articles analyzed, particularly in the "football" and "athletics" categories, cannot be ruled out. All American and Canadian publications on football in particular were checked individually to accurately distinguish between soccer and American football. If publications could not be unambiguously classified, they were excluded. For "athletics," the single "athlete" item in the title would have led to 10,866 publications, most of which were not related to "athletics" (**Table 3**). In an alternative search, specific terms related to athletics (e.g., javelin and relay) were merged, yielding a sufficiently accurate outcome. Similarly, articles with the generic term "repeated sprints" were included only if one sport was clearly mentioned in the title. There is also potential for a biased bibliometric analysis because some articles published on topics other than "exercise and sport sciences" or general medical and basic science journals could not be excluded (e.g., Olympic sports-related sociology), possibly leaving out influential works. Therefore, the present bibliometric analysis should be interpreted in light of these limitations.

Using our approach, it was not possible to differentiate research on high-level exercise from (everyday) physical activities. This limitation applies in particular to sports that occur in parallel in common everyday activities, such as walking or cycling. These categories are therefore likely overrepresented in our analysis in comparison to sports that are practiced only for competitive purposes and therefore are less frequently treated in the scientific literature. It is noteworthy that despite this bias, football still dominates the "sport sciences" field.

The absolute bibliometric is by definition correct only at the date of the search. We decided to report these absolute metrics (and not only the relative percentage values) for clarity and because it might help the reader to search beyond the top 5 articles for each sport displayed in **Tables 4**, **5**.

One additional limitation was the descriptive nature of the analysis and the lack of statistical treatment of the data. The descriptive nature of the present article was thought to be more appropriate for the 8 main outcomes presented in the discussion. The peculiarities in significant differences in the number of citations between sport A and sport B are of negligible importance and might distract the reader from the main points.

Finally, a more fundamental criticism of the applied approach concerns the importance attached to numbers of citations generated by peer-reviewed publications as a metric for assessing the research impact (Buttner et al., 2021). For the present review, general quantitative publication metrics were used to assess only the importance of the different sports in the scientific literature in this respect. Measuring and comparing the "quality" of science between sports are challenges for future research. We are aware that the use of the top 10 most cited articles (mean, max and min citations; **Figure 4**) in every sport as a metric of research quality is far from optimal. Our findings show that many factors are likely involved in determining the importance of a sport-specific scientific interest, and we do not intend to understate the importance of research that is impactful in terms of policy, economics and society. Finally, it would be interesting to relate the bibliometric data presented here to the economic weight and media exposure of these sports or the number of participants in them worldwide. Such analyses may provide further insights into why certain sports are more prominently represented in the scientific literature than others. The high scientific impact of publications, for example, on football (i.e., more articles and citations), likely does not reflect "better" scientific quality than that of publications on a less prominent sports.

CONCLUSIONS

The bibliometric analysis of all articles related to summer and winter Olympic sports published in the "sport sciences" literature provides novel insights into this research field, converging on eight key points: 1. nine sports (football, cycling, athletics, swimming, distance & marathon running, basketball, baseball, tennis, and rowing) were involved in 69% of the articles and 75% of the citations; 2. football (soccer) is the leading sport, with 19.7 and 26.3% of the total number of articles and citations, respectively; 3. team sports, especially American professional sports (i.e., baseball, basketball, and ice hockey), are the focus of prominent scientific output; 4. overall, winter sports generate comparatively minor scientific interest; 5. the greatest number of studies in the field are published in a relatively small number of "sport sciences" journals; 6. entrance into the Olympic programme may increase the scientific output of "recent" sports, although this hypothesis requires further substantiation; 7. local/cultural influences contribute to the representation of different sports in a journal's portfolio; and 8. finally, the relative distribution of six main research topics (i.e., physiology, performance, training and testing, injuries and medicine, biomechanics, and psychology) is extremely diverse across sports and provides information on the performance determinants of each sport. Overall, within the rapidly growing interdisciplinary "sport sciences" field, this bibliometric analysis provides valuable and helpful information for researchers, practitioners, and funding stakeholders to achieve future progress in the Olympic-based research agenda.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary materials, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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Match-Related Statistics Differentiating Winning and Losing Teams at the 2019 Africa Cup of Nations Soccer Championship

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This study investigated game-related statistics differentiating the winning and losings teams of matches during the 2019 African Cup of Nations (AFCON) soccer tournament. The sample consisted of 38 games, with the data obtained from the InStat Scout platform. Data were analyzed using mean (M), SD, effect size (ES), structure coefficients (SCs), and the Wilcoxon signed-rank test. The results showed that the winning teams performed significantly better than the losing teams in terms of shots ($M = 12.13$, $SD = 4.67$, $Z = -2.26$, $ES = 0.62$), shots on target ($M = 5.05$, $SD = 2.54$, $Z = -4.22$, $ES = 1.13$), and shots from counter-attacks ($M = 2.24$, $SD = 1.42$, $Z = -2.48$, $ES = 0.57$). Shots on target ($SC = 1.22$), shots ($SC = -0.73$), fouls ($SC = 0.60$), total passes ($SC = 0.44$), and yellow cards ($SC = -0.32$) presented the highest discriminatory power. These findings highlight the key match performance variables which influence the game results and may assist coaches in developing and implementing team strategies to improve the likelihood of winning the AFCON championship.

Keywords: team performance, tactics, statistics, counter-attacks, shots

INTRODUCTION

The Africa Cup of Nations (AFCON) is the largest continental soccer championship organized under the auspices of the Confederation of African Football (CAF). The first competition was held in 1957, with the following four countries competing: Egypt, Sudan, Ethiopia, and South Africa. Since 1968, the tournament has been held every 2 years, with the number of teams increasing to eight in 1968 and 12 in 1992. With the return of South Africa to the African soccer competitions in 1996, the tournament expanded to 16 teams; however, Nigeria withdrew from the competition due to political issues, thereby reducing the number of teams to 15 (Confederation of African Football, 2014; Kubayi and Toriola, 2020a). In 2019, the number of teams expanded to 24 in order to give more countries an opportunity to participate in the championship. The AFCON is rated as the most popular tournament on the continent, watched by millions of people in every African country (Njororai, 2019).

Despite the popularity of soccer in Africa (Kubayi et al., 2015), there is limited information on the match performance of national teams in the African competitions (Njororai, 2019; Kubayi and Toriola, 2020b). Currently, match analysis research in soccer is focused mainly on European competitions (Mao et al., 2016; Zhou et al., 2018). For instance, previous studies have reported that the winning teams had higher averages than the losing teams in terms of performance variables such as shots, shots on target, shots from open play, shots from counter-attacks, total passes, accurate passes, crosses, through balls, corners, dribbles, and ball possession (Lago-Peñas and Lago-Ballesteros, 2011; Lago-Peñas et al., 2011; Liu et al., 2015). In addition, the losing teams committed more fouls and received more yellow cards than their winning counterparts in Europe (e.g., Spanish La Liga, UEFA Champions League). This shows that the winning teams are primarily effective in variables related to goal scoring and retaining ball possession, which is a style of play associated with success in both the European and the international competitions (Collet, 2013; Kubayi and Toriola, 2020b).

To date, the available published data on key performance indicators in African soccer has focused on ball possession in domestic competitions (Kubayi and Toriola, 2019). For example, Kubayi and Toriola (2019) reported that the losing teams had higher ball possession than the winning teams in the South African Premier Soccer League. However, a limitation of the findings was the lack of analysis related to the potential impact of match performance indicators that can lead to team success. Due to the evolving nature of soccer, as well as the need for analysts and coaches to be informed of the current in-game performance trends, it is essential to reassess not only the possession of the ball during a match but other possible game-related statistics that may contribute to effective performance (Oberstone, 2009; Araya and Larkin, 2013).

From a continental perspective, there is little knowledge of the main performance indicators that may influence the African match results. Therefore, understanding the key match statistics is crucial, as the continent's football structure is relatively less developed and needs more scientific information (Zhou et al., 2018) to potentially inform future tactical decisions and coaching processes (Kubayi and Larkin, 2019). By understanding the current trends in team performance, coaches may be able to devise team tactics to maximize the chances of winning the competitions. Therefore, this study aimed to investigate game-related statistics that differentiated the winning and losing teams during the 2019 AFCON soccer tournament.

METHODS

Sample, Data Source, and Variables

Data of all 52 matches played during the 2019 AFCON soccer championship were obtained from the InStat Scout platform and subsequently analyzed. The competition consists of 24 teams divided into six groups of four teams. Each team plays with the other three in their group once, with three points earned for a win, one point for a draw, and zero for a loss. In every group, the winners and runners-up, as well as the four best third-placed teams, qualify for the knock-out stage of the tournament (i.e., 16 teams). The knock-out stage starts with the round of 16, followed by quarter-finals, semi-finals, third-place playoff, and the final. For the purpose of this study, the 14 matches which ended in draws were excluded from the analyses. Therefore, the final sample consisted of 38 games played during the competition. Ethical clearance was granted by the institution of the lead author's ethics committee.

Match statistics consisted of variables related to goal scoring (i.e., shots, shots on target, and shots from counter-attacks), passing and organizing (i.e., passes, percentage of accurate passes, percentage of ball possession, dribbles, and percentage of successful dribbles), and defending (i.e., tackles, percentage of tackles won, fouls, and yellow cards). The operational definitions of these variables are provided in a previous study (Lago-Peñas et al., 2011; Liu et al., 2015; Mao et al., 2016).

Reliability Testing

The inter-observer test was used to assess the reliability of the data. Two independent soccer analysts, who were not part of the research team, coded each of the four randomly selected matches (i.e., 10.5% of the sample). Thereafter, the two data sets were computed to assess the level of agreement. Cronbach's α coefficient was used to assess the reliability of the match statistics. The alpha values ranged from 0.71 to 1.00. A value above 0.70 is considered to be within the acceptable limits and reliable (Taber, 2018).

Statistical Analysis

Data were reported as means (Ms) and SDs. A Wilcoxon signed-rank test was used to compare the match statistics between the teams that won and lost. A significance level was set at $p \leq 0.05$, and the effect size (ES) was used to assess the magnitude of the differences in the mean scores of the studied variables. The ES values were categorized as follows: trivial (<0.20), small (0.20–0.59), moderate (0.60–1.19), large (1.20–2.00), and very large (>2.00) (Batterham and Hopkins, 2006). Finally, a discriminant function analysis was carried out to identify the game-related statistics that differentiated winners and losers. The structural coefficient (SC) was used to identify the performance variables that best contributed to the discrimination between winners and losers. The SC value $\geq |0.30|$ was considered to have a significant contribution between the groups (Tabachnick and Fidell, 2001). Statistical analyses were conducted using IBM SPSS Version 26.

RESULTS

Table 1 shows differences in the game-related statistics between the winning and losing teams during the 2019 AFCON soccer tournament. The findings highlighted that the winners performed significantly better than the losers for the following variables: shots (M = 12.13, SD = 4.67, Z = −2.26, $p = 0.02$, ES = 0.62), shots on target (M = 5.05, SD = 2.54, Z = −4.22, $p = 0.001$, ES = 1.13), and shots from counter-attacks (M = 2.24, SD = 1.42, Z = −2.48, $p = 0.01$, ES = 0.57). The winning teams had higher averages, although not significant, than the losing teams for defensive-related variables such as ball recovery and the tackles won.

Table 2 presents the discriminant function structure coefficients of the winning and losing teams. The findings showed that the discriminant function was statistically significant ($p < 0.05$) and correctly classified 78.9% of the cases. Match statistics variables, such as shots on target (SC = 1.22), shots (SC = −0.73), fouls (SC = 0.60), total passes (SC = 0.44), and yellow cards (SC = −0.32) had the highest discriminatory power.

TABLE 1 | Match statistics between the winning and losing teams in the 2019 African Cup of Nations (AFCON) soccer tournament.

	Win	Lose	*Z*	Sig.	ES
Goal scoring					
Shots	12.13 ± 4.67	9.47 ± 3.93	−2.26	0.02*	0.62
Shots on target	5.05 ± 2.54	2.63 ± 1.66	−4.22	0.00*	1.13
Shots from counter attacks	2.24 ± 1.42	1.42 ± 1.48	−2.48	0.01*	0.57
Passing and organizing					
Passes	421.39 ± 96.74	393.58 ± 77.51	−0.97	0.33	0.31
Accurate passes (%)	80.97 ± 4.25	79.84 ± 3.15	−1.21	0.23	0.30
Ball possession (%)	51.32 ± 8.13	48.71 ± 8.12	−0.98	0.33	0.32
Dribbles	27.08 ± 7.31	25.63 ± 6.42	−0.92	0.36	0.21
Successful dribbles (%)	14.92 ± 5.44	14.24 ± 4.34	−0.84	0.40	0.14
Defending					
Ball recoveries	50.58 ± 7.68	48.34 ± 7.67	−1.76	0.09	0.29
Tackles	32.82 ± 6.94	32.42 ± 8.55	−0.04	0.97	0.05
Tackles won (%)	56.89 ± 8.39	54.32 ± 10.69	−1.19	0.24	0.27
Fouls	19.16 ± 5.68	17.79 ± 4.59	−1.05	0.29	0.26
Yellow cards	1.37 ± 1.05	1.79 ± 0.88	−1.64	0.10	0.43

**Significant at $p < 0.05$.*

TABLE 2 | Discriminant function, SC, between the winning and losing teams in the 2019 AFCON soccer tournament.

Variables	SC
Shots on target	1.22*
Shots	−0.73*
Fouls	0.60*
Total passes	0.44*
Yellow cards	−0.32*
Shots from counter attacks	0.25
Ball possession (%)	−0.25
Successful dribbles (%)	0.20
Tackles won (%)	0.17
Tackles	0.13
Accurate passes (%)	0.09
Ball recoveries	−0.06
Dribbles	0.04
Eigenvalue	0.60
Wilks' lambda	0.62
Canonical correlation	0.61
Chi-squared	31.71
Significance	0.00
Reclassification (%)	78.9

**SC discriminant value > |0.30|.*

DISCUSSION

The main purpose of this study was to investigate the game-related statistics differentiating the winning and losing teams during the 2019 AFCON soccer tournament. The findings highlighted that all goal-scoring variables significantly discriminated between the teams that won and lost. The current study substantiates the notion that the winning teams perform better in relation to the goal-scoring performance variables compared to the losing teams (Lago-Peñas et al., 2011). Specifically, the findings showed that the winning teams had significantly greater total shots and shots on target than their counterparts. However, the magnitude of the difference was larger on the shots on target than on the total shots. Further, shots on the target had a higher discriminatory power (SC = 1.22) than the total shots (SC = −0.73). These findings are consistent with those of previous studies, which confirmed the shooting quality (i.e., accuracy) rather than the quantity that determines the match outcome in soccer (Yue et al., 2014; Liu et al., 2015; Varley et al., 2017; Kubayi and Larkin, 2020). Considering the high importance of shots on the target, coaches should consider developing training activities with a focus on shooting accuracy (Zhou et al., 2018).

In addition, it was found that the winning teams had significantly more shots from counter-attacks than the losing teams. Previous research has shown that the teams using the counter-attacking style of play tend to create more goal-scoring opportunities (Tenga et al., 2010a). This is attributed to the fact that a counter-attack quickly moves the ball into the opponent's final third of the field, which forces the defending team to immediately reorganize from an unorganized defensive structure (Kim et al., 2019). Therefore, such a style of play appears to generate a degree of imbalance in the opposition defense, which can result in goals being scored (Tenga et al., 2010b). Therefore, it is suggested that coaches should design the training programmes that encourage counter-attack play to gain a potential advantage over the opponents.

The findings from the current study also indicated that the losing teams received more yellow cards than those who won. The discriminatory power of yellow cards was SC = −0.32, indicating a negative impact on the team performance. This result corroborates with previous studies demonstrating that the number of yellow cards in the UEFA Champions League significantly discriminated between the winners and the losers (Lago-Peñas et al., 2011). Kubayi and Toriola (2020b) also confirmed that in the 2018 FIFA World Cup, the African teams were issued more yellow cards than their European counterparts, which compromised their performance. Further, the current study found that the winning teams had higher averages, albeit being nonsignificant than the losing teams for the defensive-related variables, such as ball recovery and the tackles won. These results are consistent with the previous studies, which found that successful tackles and prompt recovery of ball possession are related to team success (Almeida et al., 2014; Vogelbein et al., 2014; Liu et al., 2015). The present observations indicate that successful teams not only need to be effective in attacking but also must defend well in order to increase their chances of winning games.

The discriminant function analysis showed that the total passes had high discriminatory power. The descriptive analysis also indicated that the winning teams had a higher number of passes than those which lost. This is a key finding, as a greater number of passes may be an effective approach in building attacking a play and creating more opportunities to shoot at goal (Jones et al., 2004; Araya and Larkin, 2013). However, no significant differences were found between the winners and losers in terms of the accuracy of passes and ball possession. While a previous study has found that for the European teams, passing accuracy is strongly linked with holding on to the ball (Collet, 2013), for African matches, the ball possession does not define the successful team performance (Kubayi and Toriola, 2019). Bradley et al. (2014) also found that dominant teams in the European competitions have adopted a possession style of play, suggesting that they prefer to "control" the game by dictating the play, but if a team is unable to retain the ball possession, a "direct" style of play might be a more appropriate game tactic. This direct style quickly takes the ball into shooting positions, thereby possibly creating more goal-scoring opportunities (Kite and Nevill, 2017).

CONCLUSION

The results of the current study highlighted the game-related statistics that influenced match results during the 2019 AFCON soccer competition. The findings showed that the winning teams had a greater number of total shots, shots on target, and shots from counter-attacks compared to the losing teams. Further, shots on target, shots, fouls, total passes, yellow cards, and shots from counter-attacks had the highest discriminatory power. These results may assist the African soccer coaches in tailoring match tactics and implementing training activities to increase the chances of winning matches during the AFCON championships.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Both authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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A Scientific Perspective on Reducing Ski-Snow Friction to Improve Performance in Olympic Cross-Country Skiing, the Biathlon and Nordic Combined

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Of the medals awarded at the 2022 Winter Olympics in Beijing, 24% were for events involving cross-country skiing, the biathlon and Nordic combined. Although much research has focused on physiological and biomechanical characteristics that determine success in these sports, considerably less is yet known about the resistive forces. Here, we specifically describe what is presently known about ski-snow friction, one of the major resistive forces. Today, elite ski races take place on natural and/or machine-made snow. Prior to each race, several pairs of skis with different grinding and waxing of the base are tested against one another with respect to key parameters, such as how rapidly and for how long the ski glides, which is dependent on ski-snow friction. This friction arises from a combination of factors, including compaction, plowing, adhesion, viscous drag, and water bridging, as well as contaminants and dirt on the surface of and within the snow. In this context the stiffness of the ski, shape of its camber, and material composition and topography of the base exert a major influence. An understanding of the interactions between these factors, in combination with information concerning the temperature and humidity of both the air and snow, as well as the nature of the snow, provides a basis for designing specific strategies to minimize ski-snow friction. In conclusion, although performance on "narrow skis" has improved considerably in recent decades, future insights into how best to reduce ski-snow friction offer great promise for even further advances.

Keywords: friction, tribology, equipment, biomechanics, speed, snow, gliding, skiing

INTRODUCTION

Cross-country skiing, the biathlon and Nordic combined (for which 24% of the medals at the Beijing 2022 Olympics were awarded) all involve skiing on "narrow" skis, over a wide range of speeds (5–70 km/h) and varying terrain (with inclines of as much as 20%) (Sandbakk and Holmberg, 2014; Pellegrini et al., 2018). Cross-country skiing involves two major techniques, i.e., the classical style with its four different sub-techniques (diagonal striding, double poling, double poling with a kick, and herringbone) and skating with five sub-techniques (Gears 1-5) (Holmberg, 1996), whereas the biathlon and Nordic combined involve skating only. The different sub-techniques are utilized primarily to adapt to changes in slope and speed.

Ekström (1980) described skiing as "a relationship between man, equipment and environment and all these factors should be adapted to each other to obtain an optimal result." Basically, a skier's speed is determined by the net sum of propulsive and resistive forces, so performance can be improved by increasing the former and reducing the latter. Propulsive forces derive primarily from muscular work, which is dependent both on the topography of the course and how efficiently the skier utilizes different skiing techniques. At the same time, the variation in resistive forces, which are due to gravity, aerodynamic drag, and ski-snow friction, require the skier to adapt his/her technique as effectively as possible to maximize propulsion while minimizing resistive forces (Gløersen et al., 2018).

Acting against the resistive forces requires a considerable proportion of the total mechanical work and energy expended by a skier (Spring et al., 1988). The magnitude of the gravitational pull is determined by the skier's body weight, which remains more or less constant during any given race. The aerodynamic drag increases with speed squared and is also dependent on the size and shape of the skier's body and his/her clothing (Brownlie, 2020) and position (upright or tucked), as well as on the air density and wind conditions (Leirdal et al., 2006; Ainegren and Jonsson, 2018).

The factors that interact to influence ski-snow friction include the speed of motion, the temperature and humidity of both air and snow, as well as the crystalline nature of the snow. In addition, the stiffness and geometry of the ski, material composition, and micro-topography of the base (the structure produced by grinding/hand-rill) and ski waxing exert a major impact. Measurements carried out by Budde and Himes (2017) demonstrated that the coefficient of friction can be as low as 0.005 on transformed, hard snow and as high as 0.035 on fresh, cold snow. As in the case of aerodynamic drag, ski-snow friction increases with speed (Hasler et al., 2016; Budde and Himes, 2017), although to a lesser extent within the range of speeds normally employed during elite ski races. Mathematical modeling estimates that each decrease of 0.001 in the friction coefficient reduces the average time required to cover each kilometer of a race by ∼2 s (Moxnes et al., 2014).

Although much research has focused on the physiological and biomechanical determinants of success in cross-country skiing and the biathlon (Holmberg, 2015; Laaksonen et al., 2018), surprisingly little is known about resistive forces and, in particular, about ski-snow friction in this context. The major influence exerted by ski-snow friction on performance was demonstrated clearly by the impact of the cold and dry snow during the 2022 Winter Olympics in Beijing. Minimization of this friction to improve performance requires a more detailed mechanistic understanding of the influence of the factors described above, as well as of the forces applied by the skier to the skis and thereby to the underlying snow.

Here, we update current knowledge concerning ski-snow friction and related mechanical aspects of the interactions between the skier, skis, and snow, as well as provide perspectives on the types of investigations that are most needed to gain further insight into how best to reduce this resistive force.

KINETIC FRICTION—A MAJOR RESISTIVE FORCE

The kinetic friction encountered as a ski moves across the snow exerts a major impact on gliding and, thereby, on the skier's performance. At an average speed of 25 km/h, the skier must produce 100–140 W of power to overcome friction with a coefficient of 0.025. Mathematical modeling indicates that lowering the friction coefficient by 0.001 would reduce the time required to cover each kilometer of a race by ∼2 s (Moxnes et al., 2014), which for typical Nordic ski distances would represent a significant advantage.

An important and unavoidable component of this friction arises from adhesive and viscous shear resistance at the microscopic contact points between the snow and ski base. Viscous shear, or drag (the force required to shear a thin film of water), can be expressed as follows in terms of simple Couette flow of a Newtonian fluid sheared between two parallel surfaces without slippage:

$$F_w = A_w \eta u/h, \tag{1}$$

where A_w is the area of the region(s) that becomes wet, η and h the viscosity and thickness, respectively, of the thin film of water that forms between the ski and snow, and u the speed of the skier. This simple expression illustrates clearly that the presence of a film of water, in particular a thin film, that covers a large area beneath the skis is detrimental. The friction becomes even greater when the gap between the ski and snow is filled with water, producing patches that can be much larger than the actual points of contact (Colbeck, 1996).

The amount of energy required to overcome the adhesive and viscous components of this resistance depends largely on the temperature and humidity of both the air and snow (Bowden and Hughes, 1939; Colbeck, 1992; Colbeck and Perovich, 2004). On the other hand, at colder temperatures, when the humidity of air and snow is low, such melting may improve glide. In this case, it is important that the meltwater remains at the contact spots where the load is carried and attenuates shear resistance, while wetting and water bridging remain relatively limited. At higher temperatures, the reverse is usually the case, i.e., excess water elevates resistive forces.

THE FACTORS THAT INFLUENCE KINETIC FRICTION AND APPROACHES TO REDUCING THIS FRICTION

Figure 1 and **Table 1** summarize the contributions of the various resistive forces and the different approaches to reducing friction.

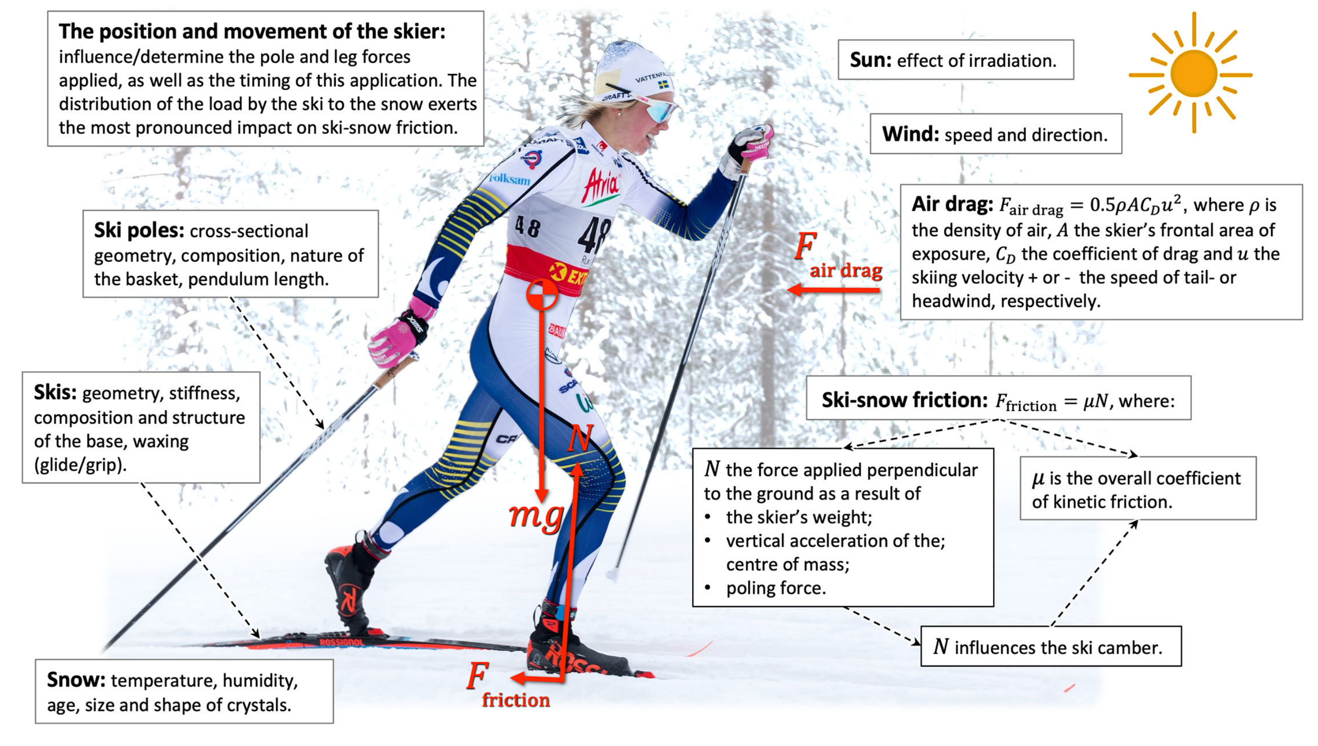


FIGURE 1 | Illustration of the resistive forces acting on a cross-country skier and factors that influence these forces.

The Nature of the Snow

The small ice crystals which often stick together to become flakes of natural snow can have a variety of different forms—including dendrites, needles, columns, and plates—depending on the temperature, humidity, and other conditions in the clouds where they are formed (Libbrecht, 2007). The snow that then covers the ground consists in general of a mixture of different crystalline forms, the composition of which is also influenced by the conditions encountered while falling to the ground (Colbeck, 1987). Moreover, since snow on the ground is always close to its melting temperature, the crystals of which it consists undergo constant transformation in size and shape. The rate of this metamorphosis depends on prevailing thermal and meteorological conditions and a common consequence is rounding off of the sharp edges of snow crystals, which allows them to bind together more extensively and form larger structures. This metamorphosis, along with the mechanical work of friction and compaction that occur while gliding over the surface, will undoubtedly cause variations in the ski-snow friction (Lemmettyla et al., 2021; Wolfsperger et al., 2021).

In contrast, machine-made snow consists of spherical water droplets that freeze from the outside. This difference is significant, since the shape of the snow crystals and the manner in which they bind to one another (i.e., the microstructure) affect the hardness and other mechanical properties of snow (Theile et al., 2009).

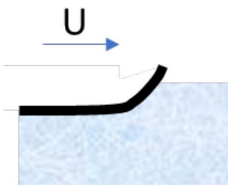
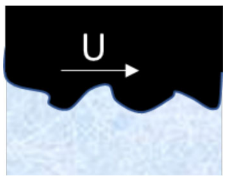
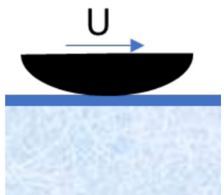
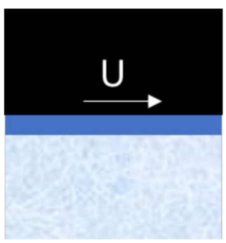
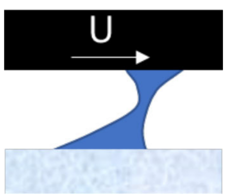
The bindings between the components of snow, referred to as sintering, can easily be broken, but then new interactions occur rapidly. Sintering increases the strength of snow, which has practical implications, e.g., with respect to the gradual hardening of a groomed ski track (Colbeck, 1997; Herwijnen and Miller, 2017).

Changes in environmental conditions can result in extensive alterations in the complex structure of natural snow, both at the macro and micro levels (Karlöf et al., 2013; Lintzén, 2016). The age of the snow and/or the metamorphic process also affect these structures. Machine-made snow is in general less variable, providing a harder surface that allows strong pushes without deep penetration by the poles or skis and, furthermore, lasts longer without melting or deterioration due to usage.

In the 1990's, for obvious practical reasons, regions with little snow began to use snow guns. During the following decades, this practice expanded greatly and today, most of the snow on which World Cup and Olympic cross-country ski races take place is a combination of natural, machine-made and stored snow (Lintzén and Knutsson, 2018), with the latter often forming the base. At the same time, improvements in the machines used to groom snow now provide harder and more homogenous surfaces that allow more rapid skiing.

Clearly, minimization of sliding friction on a ski track must take into account the predominant characteristics of the snow present, as well as factors that could potentially alter these properties.

TABLE 1 | Mechanisms that lead to and strategies for reducing friction.

Mechanism	Schematic illustration	Impact of temperature and type of snow (H = high, M = intermediate, L = low)				Strategies designed to reduce friction
		−15°C New	−1°C Old	+1°C New	+4°C Wet	
Compaction of snow in front of and under the ski		H	L	H	M	Ensure tracks with hard surfaces. Use a more flexible ski rocker. Use skis with low maximal contact pressure
Micro-plowing by irregularities in the ski base and/or surface of the snow		H	L	M	M	Ensure equal hardness of both surfaces and/or smooth surfaces
Adhesion between the ski base and the fluid surface of the snow		H	M	L	L	Minimize the number of contact spots by texturing the ski base or making the track surface very hard
Viscous shearing of a film of water		L	L	H	H	Avoid large patches of thin water films by, e.g., making deep grooves where water can drain without filling the gap between ski and snow
Water bridging involving many strong water menisci.		L	L	M	H	Maximize hydrophobicity of the ski base and/or make the track surface more porous. Use skis with small (macro level) contact zones and high camber.

The Ski Track and Its Preparation

According to the manual of the Fédéeration International de Ski (2012), a cross-country ski race course should test the skier's technical and physical abilities while providing smooth transitions between uphill and downhill sections and undulating, rolling terrain, all approximately equal in total length. The varying terrain requires frequent transitions between the nine main sub-techniques used in classical skiing and skating (Holmberg, 2015).

Preparation or grooming of a ski track involves compacting the snow under pressure (e.g., using a snow groomer or grooming equipment behind a snow mobile or ATV/UTV with tracks), which enhances sintering and increases density in a manner and to an extent dependent on the properties of the snow initially present. Modern snow groomers have gone through considerable development and now produce harder and more homogenous surfaces that allow faster skiing.

In the case of new snow, grooming accelerates the rounding and other aspects of the transformation of the components, thereby elevating the number of contact points between crystals and the sintering strength. With old snow or clusters of ice, grooming reduces particle size, which also promotes sintering and strength. Dry snow of low density may require several grooming passages, while wet snow is preferably groomed at approximately the time at which it freezes. The speed of grooming also influences the outcome, both on icy and fresh snow. When the snow layer is thin or the snow is very wet and soft, alternative approaches that exert less weight on the surface (e.g., grooming equipment behind a snow mobile or ATV/UTV with tracks) are preferable.

It requires some time for the sintering of the snow to be completed after track preparation. A temperature gradient accelerates this process, whereas grooming the snow will attenuate existing temperature differences (Colbeck, 1997; Herwijnen and Miller, 2017). Heat radiation is high on a clear night (Raman, 1935) and since this has a pronounced impact on the temperature gradient, it is best to groom in the evening, at night or during the early morning, depending on the snow type and temperature. The time required for sintering, both before and after track preparation, depends on the snow conditions. If the weather is warm, snow hardeners such as salt can help achieve the desired strength and hardness (Kobayashi et al., 2000).

Moreover, grooming of a track also needs to be adapted to the type of competition that is to take place (Fauve et al., 2010). Classical ski tracks are prepared with track setters 2–5 cm deep and follow, in general, the ideal trajectory of skiing, which is usually in the middle of the course (with the exception of curves). In the case of skating, the sub-techniques of which require more space, there is no need for track setters, but the course needs to be considerably wider (a minimum of 4 m and as much as 9 m on uphill sections of mass start races).

The Skis

In general, Olympic skiers own 30–50 pairs of skis specialized for snow of different temperatures and conditions (Breitschädel, 2012), of which <25% are used regularly (Pellegrini et al., 2018). These skis are composed of polyethylene plastic, fiberglass, and carbon fiber and are characterized by a camber that separates the gliding zones at the front and rear. Moreover, 10–15 different types of bases with properties suited specifically for different snow conditions are utilized by elite skiers.

The characteristic of the ski that influences ski-snow friction most is its camber, which determines the areas of the ski that carry most of the load. Since the microstructures of both the ski base and surface of the snow are irregular, only a small proportion of the base is in contact with the snow. If the area of these contacts is too small or the contacts are too few in number, the contact pressure is high and the irregularities will give rise to friction (Glenne, 1987; Scherge et al., 2013). The heat generated by friction promotes melting, which is likely to increase the viscous shear resistance while reducing the adhesive component (see also above).

The ski base is composed of polyethylene, which is highly hydrophobic, thereby eliminating strong interaction with water menisci, while being tough enough to endure abrasion by snow crystals. In addition, to reduce friction and thereby improve gliding considerably, the microstructure of the ski base surface is prepared by stone grinding (Breitschädel, 2015), or other manual procedures designed to achieve an effective balance between the regions that bear the load and grooves that cannot fill up with water, thereby avoiding viscous drag.

The optimal balance varies for each different type of snow. The optimal size of the small regions of contact (the micro-level) depends on the smoothness of that part of the ski base that makes first contact with the track. If the combined area of all the small regions of contact is too small, the ski base may plow into the snow surface, producing resistance. Viscous drag can be reduced by increasing the number and depth of microscopic grooves with a hand-held rill, which increases the average distance between the ski and snow.

In addition, application of various waxes that promote glide and/or grip, depending on snow conditions, improves performance. In this context, hydrophobic waxes repel moisture, thereby significantly reducing friction due to the potential presence of a layer of water. For classical skiing, both grip and glide wax are needed, whereas skating is optimal with glide wax only.

Today's national teams devote considerable resources to paying highly specialized staff to prepare the skis. Indeed, all major skiing nations have special waxing trailers where preparation can be optimized using advanced technology, in a manner similar to the teams involved in Formula 1 and professional cycling competitions. Moreover, large variations in the conditions at different competition venues may necessitate long periods of preparation between different championship events.

In general, when the snow is soft, pressure must be minimized to reduce compaction and plowing, both macroscopically as the ski sinks into the snow and plows/presses it forward, and microscopically as the ski base plows into the surface of the snow (Mössner et al., 2021). At the same time, as indicated by Equation (1) above, the area over which the ski base and snow are in close proximity must be minimized in order to avoid large wet patches (Glenne, 1987; Nachbauer et al., 2016; Butler and Vella, 2022).

In addition, different brands of skis might interact with the snow in different ways, so that even the choice of brand could influence performance significantly under certain snow conditions. To minimize friction, the characteristics of the skis must be chosen to deal with prevailing considerations as effectively as possible. Clearly, within the limits set by environmental regulations, considerable effort and resources will be directed toward optimizing the design and material composition of cross-country skis and, in particular, of their base even further.

Interactions Between the Snow, Track, Skis, and the Skier

Whatever its nature (classical or skating, sprint or distance), each individual ski race involves a unique combination of track topography, weather, and snow conditions (including local variations along the course). To improve performance, skiers can adapt to these conditions in a number of different ways, including their choice of sub-technique. An obvious example is choosing to utilize the double poling technique during an entire classical race, which allows the use of skis without grip wax and, thereby, more optimal glide. In contrast, diagonal stride and double poling with kick require an appropriate balance between adequate grip and excellent glide.

Ski skating is somewhat less challenging for ski technicians, since this technique requires primarily maximal gliding. At the same time, certain elite skiers have developed modified sub-techniques, such as diagonal running uphill with a more rapid, forceful leg kick/thrust, which allows the use of shorter/less grip and/or stiffer skis and, consequently, better glide (Pellegrini et al., 2018). When conditions vary along the course, glide/grip should be optimized for those sections on which the skier is the weakest while, at the same time, ensuring favorable conditions where he/she is most efficient. In all cases, a good subjective "feeling" that the skis are well-suited to the specific conditions is also a concern.

Moreover, ski-snow friction is influenced by the technical ability and physical characteristics of each individual skier. For example, skiers who weigh less and demonstrate superior technique can sometimes utilize relatively stiffer classical skis and/or shorter/less grip wax than heavier skiers. Moreover, in connection with ski skating, some skiers, often those with less favorable biomechanical characteristics, more often complain that their poor glide on cold/wet snow, due to extensive friction, detracts from their overall performance.

CONCLUDING REMARKS AND FUTURE DIRECTIONS

To date, most research on ski-snow friction has been empirical and based on extensive trial and error, resulting in experience-based knowledge concerning the optimal approaches to reducing friction under various conditions. Unfortunately, due to the lack of rigorous scientific evidence, the optimal parameters on which to base the choice and preparation of the skis remain extremely unclear.

Here, our focus has been specifically on the influence of ski-snow friction on performance in Olympic sports that involve cross-country skiing. However, improved knowledge of tribology can also have important implications for other winter sports as well. To varying extents, ski-snow/ice friction have helped determine the winners of 56% of the medals awarded at the Winter Olympics in Beijing—not only in cross-country, alpine and freeskiing and snowboarding, but also in skating, sledding, and the team sports curling and ice hockey, which all take place on ice.

The list of *future requirements* below indicates the further knowledge required for more effective reduction of resistive forces and consequent improvement in the performance of elite cross-country skiing, the biathlon, and Nordic combined:

- A procedure for measuring ski-snow friction under real conditions (speed, temperature, snow, skis) with very high accuracy, since, as mentioned above, differences in the coefficient of friction as small as 0.001 may exert a significant impact.
- Development of new, environmentally acceptable waxes that reduce ski-snow friction even more effectively.
- Determination of the role of friction throughout an entire cycle of skiing, e.g., of double poling.
- Standardization of the testing of skis prior to a race. Friction is often determined while the skis are gliding freely with a static load, conditions that are present only when skiing downhill.
- Provision of more detailed information to the technicians involved in ski preparation and to coaches for evaluation of performance. This could be accomplished by utilizing sensor technology to monitor the speed and utilization of different sub-techniques by individual skiers on various types of terrain and sections of the course.
- Prediction of the optimal properties of skis for any given skier and race. For example, classical skiing optimization of the tradeoff between a stiffer ski with wax with greater grip vs. a softer camber with wax that produces less drag remains challenging.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author/s.

AUTHOR CONTRIBUTIONS

AA, H-CH, and RL initiated this work. BP, NL, and NE subsequently became involved. All authors contributed to the conception and design of figures and tables, as well as to writing and revising the text prior to submission. They all qualify for authorship and have approved the version of the manuscript submitted for publication.

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Gait and Neuromuscular Changes Are Evident in Some Masters Club Level Runners 24-h After Interval Training Run

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Purpose: To examine the time course of recovery for gait and neuromuscular function immediately after and 24-h post interval training. In addition, this study compared the impact of different statistical approaches on detecting changes.

Methods: Twenty (10F, 10M) healthy, recreational club runners performed a high-intensity interval training (HIIT) session consisting of six repetitions of 800 m. A 6-min medium intensity run was performed pre, post, and 24-h post HIIT to assess hip and knee kinematics and coordination variability. Voluntary activation and twitch force of the quadriceps, along with maximum isometric force were examined pre, post, and 24-h post significance HIIT. The time course of changes were examined using two different statistical approaches: traditional null hypothesis significance tests and "real" changes using minimum detectable change.

Results: Immediately following the run, there were significant ($P < 0.05$) increases in the hip frontal kinematics and coordination variability. The runners also experienced a loss of muscular strength and neuromuscular function immediately post HIIT ($P < 0.05$). Individual assessment, however, showed that not all runners experienced fatigue effects immediately post HIIT. Null hypothesis significance testing revealed a lack of recovery in hip frontal kinematics, coordination variability, muscle strength, and neuromuscular function at 24-h post, however, the use of minimum detectable change suggested that most runners had recovered.

Conclusion: High intensity interval training resulted in altered running kinematics along with central and peripheral decrements in neuromuscular function. Most runners had recovered within 24-h, although a minority still exhibited signs of fatigue. The runners that were not able to recover prior to their run at 24-h were identified to be at an increased risk of running-related injury.

Keywords: gait, biomechanics, neuromuscular function, high intensity interval training, kinematics, muscle strength, running, coordination variability

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INTRODUCTION

Recreational running has seen a second boom in the early 2000s throughout Europe and North America (Scheerder et al., 2015), contributing to the growing popularity of recreational club running, with middle aged runners aged 34 and 54 years old forming 43% of road race competitors (Running USA, 2020). To improve their performance, these runners often train up to six sessions per week (Enoksen et al., 2011; Zinner et al., 2018), typically performing a combination of medium intensity continuous runs and high-intensity interval training (HIIT) (Enoksen et al., 2011; Wen et al., 2019). This growth in popularity has also contributed to the rise in the incidence of running-related overuse injuries (RROI). Videbaek et al. (2015) found that recreational runners sustain 7.7 RROI per 1,000 h of running, while van Gent et al. (2007) reported an incident rate of 19.4% to 79.3% following an examination of incidence rates across prospective, cross sectional, retrospective, and randomised clinical trials. A retrospective survey ($N = 1145$) of middle-aged (47 $\pm$ 11 years) recreational runners revealed that 49.8% were injured of whom 94% continued running despite experiencing pain (Linton and Valentin, 2018). Reducing injury rates in this group of runners would, therefore, have a widespread impact, however, understanding the aetiology of RROI remains a challenge and requires extensive examination.

Bertelsen et al. (2017) recently proposed a framework to explain RROI. Within this framework, RROI occurs when the tissue-specific load capacity is exceeded. The tissue-specific load capacity is a dynamic entity, reflecting the ability of the musculoskeletal system to tolerate load without getting injured. It reduces within and recovers between training sessions. Whether a runner exceeds this capacity will depend on their initial status at the start of the training session, which is heavily influenced by their level of recovery from previous training and the tissue-specific cumulative load experienced during their run. This cumulative load during the run is the product of the load per stride, the distribution of the load over the tissue structures per stride, and the number of strides taken [see Bertelsen et al. (2017) for a detailed description]. The load per stride is the impact force experienced which the neuromuscular system must control and distribute across the musculoskeletal system. If the accumulation of these repeated impact forces exceeds the runner's ability to control or tolerate them, then fatigue, defined as the inability to maintain an expected power output, will occur (Gandevia, 2001; Enoka and Duchateau, 2016). Fatigue could affect the control of gait mechanics and /or the distribution of the load across the tissue structures, thereby increasing the RROI risk.

Avoiding RROI requires the application of the correct training load relative to the athlete's state of recovery. This requires an understanding of both the extent of fatigue experienced within, and the time course of recovery between, training sessions. Traditionally, fatigue within a session has been considered metabolic, due to either substrate depletion or metabolite accumulation (Enoka and Duchateau, 2016). However, as runners fatigue, changes in both running gait and neuromuscular function have been observed. Fatigue-induced changes in gait have been shown in the frontal plane, for example, hip adduction angle. These changes in gait with fatigue are usually detectable after extreme fatigue, or more likely exhaustive exercise e.g., after a prolonged run to exhaustion or race (Nicol et al., 1991b; Millet et al., 2002, 2003; Place et al., 2004; Dierks et al., 2008; Bazett-Jones et al., 2013). Runners seldom undertake such exhaustive events, most of their running consists of training sessions, which although sometimes hard, are seldom to exhaustion. Training frequency far outweighs that of competing, meaning runners are more likely to sustain a RROI within training. Despite this, there has been a limited examination of the fatigue experienced during typical training sessions. Riazati et al. (2020) examined the effect of medium intensity continuous runs and HIIT on gait and muscular strength. They reported gait and strength decrements following both training types, with HIIT inducing greater changes. Compared to healthy runners, injured runners with patellofemoral pain syndrome (PFPS) or iliotibial band syndrome (ITBS) show greater hip frontal plane movement (Noehren et al., 2007, 2014; Dierks et al., 2008; Powers, 2010). The gait of these injured runners is similar to that seen in healthy runners as they fatigue, which would support the hypothesis that fatigue-induced changes in gait increase the risk of RROI.

Changes in gait with fatigue, are not just limited to joint angles and ranges of motion, there are also changes in movement coordination and variability (Chen et al., 2020). Increases in variability have been associated with a reduced ability to tolerate force absorption following ground contact (Mizrahi et al., 2000), potentially increasing injury risk (Baida et al., 2018). Furthermore, changes in variability could reflect a loss of movement control (Nordin et al., 2017). A reduction in maximal knee extensor (KE) isometric strength found during the last 5-km of a 20-km time trial, was highly correlated ($r = 0.70$) with voluntary activation of the KE measured by twitch interpolation (Ross et al., 2010). The aetiology of changes in gait kinematics, coordination variability, load tolerance, and muscle force production is not fully resolved, but likely has both central and peripheral components i.e., proximal and distal to the neuromuscular junction. Following marathon and ultra-marathon races, both central and peripheral mechanisms of fatigue are evident; subsequent recovery can take several days. As previously noted, these are extreme events and do not reflect regular training. The extent and time-course of recovery for both central and peripheral mechanisms following typical training sessions warrant further investigation. Failure to recover from a previous training session would result in a decrease in the specific load capacity within Bertelsen's model, thereby increasing the risk of developing an RROI.

Traditionally, exercise scientists have examined changes in gait, whether due to fatigue or some other intervention, using null-hypothesis statistical tests (NHST). Considerable inter-individual variation in fatigue response was found post marathon (Nicol et al., 1991a), with runners showing changes in gait both above and below pre-marathon values. Null-hypothesis statistical testing uses grouped data to identify an overall response; the nuances of the inter-individual responses are thereby overlooked. Differentiating real change from random variation is problematic when trying to identify individual responses. Minimum detectable change (MDC) offers a potential solution; it is a confidence interval approach based upon test–retest reliability. Where an individual changes by more than MDC, this would represent a real change. Recently, Riazati et al. (2020) and Bramah et al. (2021) used this approach with the former reporting different findings when using NHST and MDC approaches.

Fatigue, both multifactorial and transient, comprises of central and peripheral components. This study had dual aims, firstly to identify these multifactorial changes using gait kinematics, coordination variability, muscle force production, and muscle activation immediately post and 24-h after a typical high-intensity interval session in middle aged recreational club runners. Secondly, to compare and contrast the effect of using two different statistical approaches (NHST and MDC) to detect these changes.

METHODS

Research Design

A time-series design was used to observe changes in neuromuscular function, force production, kinematics, and running coordination variability pre, post, and 24-h post a HIIT session. It was neither feasible nor appropriate, to perform a HIIT session on consecutive days. Recreational masters age group club runners tend to run at a range of different intensities to improve performance and are likely to perform a medium intensity continuous run the day following a high intensity session (Zinner et al., 2018). A standard pace run (SPR) was, therefore, used pre, immediately post, and 24-h post HIIT to examine changes in kinematics and running coordination variability at a common speed.

Participants

Following an *a priori* power analysis based on the kinematic variables in Riazati et al. (2020) ($\alpha = 0.5$ and $\beta = 0.20$; desired effect size of 0.66) and subsequent institutional ethical approval, 20 healthy, experienced (running for at least 2 years), recreational masters age group club distance runners (N = 10 male; N = 10 female) were recruited (see **Table 1**). All the runners trained regularly, participating in HIIT, or similar type training session, at least once a week, most weeks, at their running club. All runners in this study performed between one to two HIIT sessions per week and also completed races ranging from 5 K to ultra-marathons. **Table 1** shows participant characteristics, treadmill speeds, and interval duration. Participants were excluded if they had not competed in an organised race within the previous 2 years, were not part of an affiliated running club, or had experienced any type of lower extremity injury that prevented them from running for more than a week in the past 6 months. Further exclusion criteria included any cardiovascular or neurological conditions or an allergy to the adhesive material. Medical history was pre-screened via a self-reported questionnaire; eligible participants provided informed written consent prior to testing sessions.

TABLE 1 | Descriptive characteristics of participants along with speeds, durations, $\dot{v}o_2$ max represented as mean ± standard deviation for both Hight-Intensity Interval Training session (HIIT) and standard pace run (SPR).

	Female (*n* = 10)	**Male (*n* = 10)**
Age (years)	43.2 ± 4.5	43.0 ± 5.0
Height (cm)	165.5 ± 6.4	176.5 ± 7.8
Mass (kg)	61.4 ± 11.4	78.3 ± 9.3
HIIT Speed ($m.s^{-1}$)	3.9 ± 0.4	4.3 ± 0.5
HIIT rep duration (min:sec)	03:24 ± 20(s)	03:10 ± 22(s)
SPR pace ($m.s^{-1}$)	3.1 ± 0.3	3.4 ± 0.4
$\dot{V}O_2$ max ($ml.kg^{-1}.min^{-1}$)	52.5 ± 6.2	55.3 ± 5.0

Procedure

Each runner visited the laboratory three times (see **Figure 1**). Visit 1 was a preliminary session to determine the intensities for the HIIT and SPR and familiarise runners with hip strength and electrical stimulation (E_{Stim}) procedures (see **Figure 1**). During visit 2, hip strength and E_{Stim} were measured pre and immediately-post HIIT. Gait kinematics were measured during SPR conducted before and immediately after the HIIT. During the final visit, 24-h post HIIT, runners again completed measures of hip muscular strength, the E_{stim} protocol, and SPR. All sessions were conducted at the same time of day to minimise diurnal variation (Reilly and Garrett, 1998). Runners were asked to wear the same footwear throughout and follow their habitual dietary regimen while refraining from high volume or intensity training within 48 h before testing They were also asked to refrain from any activity following the HIIT session prior to 24-h post assessment.

Preliminary Testing

Initial measurements of mass, stature, and all kinanthropometric measures were taken according to ISAK guidelines, by an ISAK qualified practitioner. Runners completed an incremental treadmill (ELG2, Woodway, Germany) test to determine maximum steady state and $\dot{V}O_2$ max. Expired gases were analysed using a Cortex Metalyser 3B (Leipzig, Germany), calibrated according to the manufacturer's instructions prior to each test. A 5-min warm-up run was completed prior to testing.

The sub-maximal test consisted of a series of incremental 4-min stages at a 0% gradient, separated by a 60-s recovery (Smith and Jones, 2001). Between stages, a fingertip capillary blood sample was taken for analysis of blood lactate concentration (Biosen C-line, EKF diagnostics, Germany). Running speed increased by 1 $km{\cdot}h^{-1}$ per stage until lactate turnpoint (LTP) was exceeded. LTP was defined as a second, steeper, more sustained, rise in blood lactate (Smith and Jones, 2001) and used to identify a maximum steady state. Following a 15-min recovery, participants completed a $\dot{V}O_2$ max test, with the initial speed set at 4 $km{\cdot}h^{-1}$ below the speed at LTP, again 0% gradient was used throughout. The treadmill speed increased by 0.5 $km.h^{-1}$ every 30 s until volitional exhaustion occurred. Breath by breath $\dot{V}O_2$ data were 30-s averaged; the highest value was taken as $\dot{V}O_2$ max (Billat et al., 2001; Midgley et al., 2006).

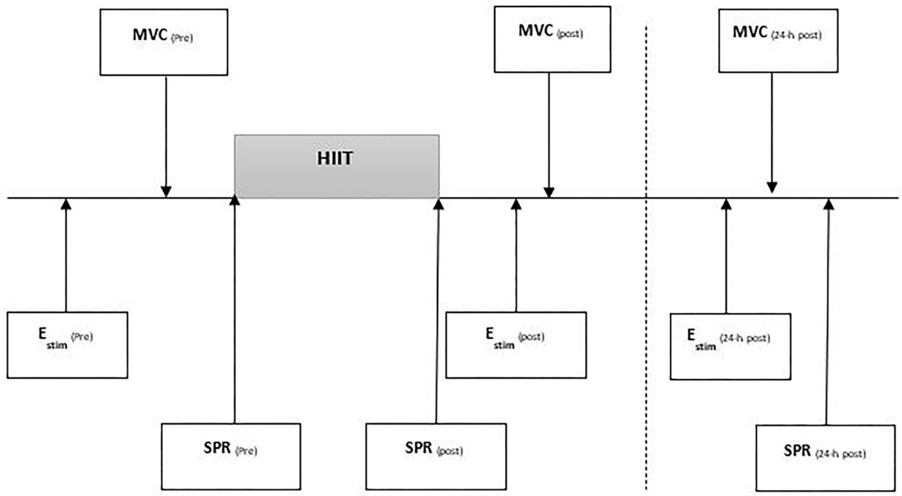

FIGURE 1 | Testing procedure outlining timing of examination of the protocol containing electrical stimulation (E_{stim}), maximal voluntary contraction (MVC) for hip and knee strength testing, standard pace run (SPR). All tests performed pre, post, 24-h post a high intensity interval training run (I-MT).

Setting HIIT and Standard Paced Run Speeds

All runs were performed on a treadmill (ELG2, Woodway, Germany). Treadmill running has been shown to be comparable to overground running (Hooren et al., 2020), and offers a level of data capture not possible in a more, ecologically valid field-based setting. The duration and speed of both HIIT and SPR were individualised based on the individual's speed at $\dot{V}O_2$ max ($s\dot{V}O_2$ max) and LTP (*s*LTP). The HIIT session was a protocol previously shown to cause fatigue (James and Doust, 2000; Riazati et al., 2020), while all runners ran the same distance, the time taken to complete the HIIT was different (see **Table 1**). It consisted of six 800-m repetitions at 1 km·h^{-1} below $s\dot{V}O_2$ max with a 1:1 work: rest ratio. The recovery was active, with participants walking at 4 km·h $^{-1}$. The SPR was halfway between the speed of lactate threshold, the first rise in blood lactate above baseline, and *s*LTP. The repetition speed was determined from a regression equation generated by plotting the averaged final minute $\dot{V}O_2$ for each 4-min stage against RS from the sub-maximal test. This relationship was extrapolated up to $\dot{V}O_2$ max to identify the speed at $\dot{V}O_2$ max (s$\dot{V}O_2$max). The speed of the repetitions was identified as 1 km·h^{-1} under s$\dot{V}O_2$ max. replicating James and Doust (1998).

Hip Muscular Strength

In order to examine muscle function and fatigue, maximum isometric force generating capability was examined (Gandevia, 2001) in the hip musculature pre, immediately-post, and 24-h post HIIT. A handheld dynamometer (Lafayette Instruments, IN, USA) was used to measure maximum voluntary isometric contraction (MVC) at the hip and knee. The handheld dynamometer was secured on the limb of the runner using a Velcro strap; furthermore, a non-elastic strap was placed around an examination table to remove tester strength bias. All hip testing positions were in accordance with Bazett-Jones et al. (2013) and included testing for hip abduction, adduction, extension, flexion, internal rotation, and external rotation, performed in respective order. Participants were asked to perform one set of three maximal effort trials for each movement in a 5-s ramp protocol, exerting maximum force against the dynamometer during the final 3 s. The highest value was recorded. There was 30 s of rest between each effort and a 1-2 min of rest between each muscle group (Bazett-Jones et al., 2013). The strength measures were recorded in Newtons and normalised to body weight (Bazett-Jones et al., 2013; Riazati et al., 2020). Measurements of lateral epicondyle to greater trochanter were used for hip strength measure normalisation.

Neuromuscular Function Assessment

Electrical stimulation of the femoral nerve was used to assess the contribution of the central and peripheral mechanisms towards neuromuscular fatigue and recovery of the quadriceps (Brownstein et al., 2017). These measures were taken pre-SPR, immediately post (within one minute of completing the HIIT), and 24-h post HIIT.

A calibrated load cell (RDP load cell model RLT; Wolverhampton, UK) was attached to a fixed custom-built isometric force chair and attached to the runner's leg at the superior malleoli via a noncompliant cuff. The load cell was used to record muscle force (N) during maximum voluntary contraction (MVC) of the knee extensors. The isometric force chair was situated near the treadmill to ensure a rapid examination of neuromuscular function following the HIIT session. Immediately following the HIIT session, runners dismounted the treadmill, and hip markers were removed to connect electrodes for the motor nerve stimulation. Participants were seated in the custom-built chair with their hips and knees flexed to 90°; this process took no longer than 30 s.

To examine central drive, voluntary activation (VA) via motor nerve stimulation and potentiated quadriceps twitch force ($Q_{tw,pot}$) were examined. In addition, the amplitude of the $Q_{tw,pot}$ can be used to measure the contractile function of the muscle, providing an added measure for the peripheral drive (Brownstein et al., 2017). Muscle fatigue was observed from a drop in force production from the maximal voluntary contraction of the KE, along with the isometric strength assessments of the hip musculature previously explained.

Single and paired transcutaneous electrical muscle stimulation (100 Hz) was delivered to the right knee extensor via a constant-current stimulator (DS7AH, Digitimer Ltd., Hertforshire, UK). Circular 5-cm self-adhesive surface electrodes (model number, Nidd Valley Medial Ltd., North Yorkshire, UK) were used and the position of the electrodes was placed over the nerve in the femoral triangle, with the anode placed between the greater trochanter and the iliac crest (Weavil et al., 2015). The electrodes were also marked with indelible ink to ensure repeatable, consistent placement for post and 24-h post measurements. Electrical stimulation was delivered at rest to the relaxed muscle, beginning at 20 mA and increased incrementally, in a stepwise fashion by 20 mA, until a plateau occurred in quadriceps twitch amplitude (Q_{tw}, N). This was performed only once on each visit; right at the start. The plateau intensity was then increased by 30% to ensure supramaximal stimulation. Subsequently, runners completed six isometric MVCs of the knee extensors with a duration of between 3 and 5 s, separated by 60 s of rest. During the final three MVCs, paired electrical stimuli (100 Hz) were delivered during, and 2-s post, contraction to assess VA. Single pulse electrical stimuli were delivered 5-s post MVC to assess quadriceps potentiated twitch force ($Q_{tw,pot}$). Voluntary activation was quantified by comparing the superimposed twitch force (SIT) during MVC with the amplitude of the $Q_{tw,pot}$ elicited 2-s after MVC at rest (Goodall et al., 2014; Brownstein et al., 2017). Voluntary activation percentage was expressed as:

$$VA\ (\%) = [\ 1 - \left(\frac{SIT}{Q_{tw,pot}}\right) x\ 100] \tag{1}$$

In our laboratory, the interclass correlation (ICC) scores for neuromuscular function are r = 0.98, 0.86, and 0.88 for MVC, VA, and $Q_{tw,pot}$, respectively (Brownstein, 2018).

Motion Analysis

Running mechanics were captured during each SPR using a 14-camera 3-dimensional motion analysis system (T-120/T-140; Vicon Motion Systems Ltd., Oxford, England) sampling at 250 Hz and calibrated before each session. The data were recorded using a lower body Plug-in Gait model following the procedure of Riazati et al. (2019, 2020). Retroreflective markers were placed bilaterally on the anterior superior iliac spine, posterior superior iliac spine, thigh, lateral epicondyles of the femur, lateral shank, lateral malleoli, base of the 2nd metatarsal, and calcaneus. The markers were carefully placed by the same researcher throughout, the desired markers were secured with double sided tape and the surrounding base was also taped down with double sided tape. Wand markers were used for the thigh and shank to obtain rotational movements of the joints. Runners wore compression leggings, with holes cut to allow markers to remain visible, to ensure the markers remained in place. The hip markers were taped around the hip, to ensure they remained in place throughout the run, using soft adhesive tape to avoid impeding hip movement. Static capture was performed 3 s prior to treadmill running sessions. This was processed using the static Plug-in Gait model and static subject calibration. During the SPR, motion analysis of kinematics and coordination variability data were recorded for 25-s at the end of the first minute.

Data Analysis

All markers were labelled and marker trajectories were filtered using a fourth order low-pass Butterworth Filer via a dynamic plug-in gait model with a 6 Hz cut-off frequency, within the motion analysis software (Nexus 2.0, Vicon Motion Systems Ltd, Oxford, England). Gait identification was achieved through visual inspection of foot strike and toe off for 20 consecutive strides (Riazati et al., 2019). Maximum angle (max) and range of motion (RoM) of the hip and knee in the sagittal and frontal planes, during the stance phase, were extracted. All processed motion analysis data were analysed using a custom script in Matlab (2018a, The Mathworks, Inc. Natick, MA, USA).

Coordination Variability

Coordination variability of interactions between sagittal (flexion/extension) and frontal (abduction/adduction) planes of motion for the hip and knee joint couplings were analysed using continuous relative phase variability (CRPV) and coupling angle variability (CAV) through vector coding. The selection of these two applications of dynamical system theory for variability was based on Miller et al. (2010), who found that both were valid methods for examining running variability. All variability analyses were processed using a custom script in Matlab (2018a, the Mathworks, Inc, Natick, MA, USA).

For both CRPV and CAV, interactions of the hip and knee joints were examined during treadmill running from 20 consecutive stance phase cycles. For full details of the procedures see Riazati et al. (2020).

Statistical Analysis

To examine the effects of the HIIT immediately and 24-hr following, this study used two statistical approaches: null hypothesis testing for group examination and minimum detectable change for individual assessment.

Null Hypothesis Testing

All data were checked for normality using Q-Q plots and deemed normally distributed. Mean and standard deviation was calculated for all variables. A one-way repeated measures ANOVA was used to assess changes over time for kinematics and joint coupling variability during SPR in addition to strength and neuromuscular function. Where appropriate Tukey's LSD test was used *post hoc*. Data were tested for sphericity using Mauchly's test. Effect sizes were calculated according to Cohen (2013) and interpreted as small (≥ 0.2), moderate (≥ 0.5), and large (≥ 0.8). The level of significance was set at $P < 0.05$. All statistical analyses were performed in SPSS v22.0 (SPSS Inc., Chicago, IL, USA).

Minimum Detectable Change

Minimum detectable change was calculated using the method of Weir (2005). An individual was considered to have fatigued when their scores immediately post or 24 h post HIIT, had changed by more than, or equal to, MDC set at a 95% confidence interval. The MDC were derived from our own reliability data, the tables are attached to the **Supplementary Files 1–4** (SDC 1-4, SEM, and MDC values for measures of muscular strength, kinematics, and variability).

RESULTS

Muscular Strength

Null Hypothesis Testing

All muscular strength measures decreased significantly with time following the HIIT (see **Table 2**) showing small to moderate effect sizes. Hip internal rotators declined over time ($F_{2,19} = 9.50$, $P = 0.001$) with a 10.8% reduction in strength post HIIT, remaining unchanged at 24-h post (10.4%), *post hoc* analysis revealed a significant reduction both post ($P < 0.001$, d = 0.39) and 24-h post ($P = 0.009$, d = 0.42). In hip abduction strength, there was significant reduction with time ($F_{2,19} = 34.14$, $P < 0.001$). Runners exhibited an 11.2% reduction in hip abduction strength post HIIT ($P < 0.001$, d = 0.41) with minimal recovery the following day (9.5%), ($P < 0.001$, d = 0.41). Hip adduction strength was reduced significantly with time ($F_{2,19} = 18.5$, $P < 0.001$), at post ($P < 0.001$, d = 0.37) and 24-h post ($P = 0.002$, d = 0. 26). A significant reduction was found in hip external rotator strength with time ($F_{2,19} = 9.54$, $P < 0.001$), there was a 12.8% reduction post HIIT ($P < 0.001$, d = 0.47), however this decline (5.8%) was no longer significant at 24-h post ($P = 0.267$, d = 0.23). Likewise, hip flexion strength showed a decline with time ($F_{2,19} = 25.94$, $P < 0.001$), while *post hoc* analysis showed significant reduction post HIIT (11.3%) ($P < 0.001$, d = 0.39) but not at 24-h post (9.1%) ($P = 0.051$, d = 0.34).

Minimum Detectable Change

The use of MDC showed that two runners had reduced hip abduction strength after HIIT beyond MDC, while three runners experienced a reduction beyond MDC at 24-h post. In hip internal rotation, three runners exceeded MDC immediately post HIIT but all had recovered by 24-h post. Post HIIT, two runners experienced a reduction in hip external rotation above MDC. Of these, one runner experienced a further drop at the 24-h post, while the other had recovered. For force measures of hip adduction and hip flexion, no runner reduced force below MDC at any time point.

Neuromuscular Function

Null Hypothesis Testing

Runners showed decrements within all neuromuscular function measures (see **Table 3**). Knee extensor MVC showed a significant reduction in force production over time ($F_{2,13} = 19.74$, $P < 0.001$). Force production declined by 8.1% ($P < 0.001$, d = 1.21) pre to immediately post HIIT and remained 3.2% lower 24 h -post ($P = 0.022$, d = 0.15). Similarly, $Q_{tw,pot}$ exhibited a significant reduction over time ($F_{2,14} = 4.08$, $P = 0.017$). Quadriceps potentiated twitch force was reduced from pre to immediately post HIIT ($P = 0.013$, $d = 0.56$), but had recovered by 24-h post ($P = 0.393$, $d = 0.12$). There was a significant change in VA over time ($F_{2,14} = 17.25$, $P < 0.001$) suggesting runners were affected by central fatigue. Voluntary activation dropped 7.3% from pre to immediately post ($P < 0.001$, $d = 1.07$), recovering to a 2.0% deficit ($P = 0.013$, $d = 0.37$).

Minimum Detectable Change

Analysis of individual KE MVC scores revealed that six runners had reduced force production beyond MDC immediately post HIIT, with only one runner recovering at 24-h post. For $Q_{tw,pot}$ immediately post HIIT, eight runners exhibited a reduction larger than MDC, with two of them failing to recover 24-h later. Furthermore, VA% dropped by more than MDC for 15 runners, with four runners still remaining impaired at 24-h post. Two runners exceeded MDC for all neuromuscular function measures at both post and 24-h post.

Kinematics

Null Hypothesis Testing

There was a significant increase in both hip maximum angle ($F_{2,19} = 11.05$, $P = 0.001$) and RoM ($F_{2,19} = 17.39$, $P < 0.001$) in the frontal plane (see **Table 4**). For maximum angle, *post hoc* analysis revealed a large increase in hip adduction both immediately post ($P < 0.001$, $d = 0.91$) and at 24-h post ($P < 0.001$, $d = 0.86$). Similarly, for RoM angle, there was a large increase in hip adduction during SPR immediately-post ($P < 0.001$, $d = 0.85$) which, although slightly reduced, remained elevated at 24-h post ($P < 0.001$, $d = 0.74$).

Knee kinematics showed a main effect for time in sagittal plane RoM ($F_{2,19} = 5.32$, $P = 0.015$, $d = 0.38$) and frontal plane maximum angle ($F_{2,19} = 3.65$, $P = 0.046$, $d = 0.74$). *Post hoc* analysis failed to show a significant change either immediately post, or at 24-h post, compared to baseline for either variable.

Minimum Detectable Change

Individually, 11 runners exhibited fatigue effects with an increase in hip frontal plane maximum angle post HIIT. Twenty-four hours later, nine runners were still showing signs of fatigue; more than any other kinematic variable. Seven runners experienced an increase above MDC for hip frontal plane RoM immediately post HIIT, with three still exceeding MDC 24-h post. Two runners experienced changes beyond MDC for hip sagittal plane maximum angle immediately post HIIT; one higher, the other lower. However, 24-h later, the runner with elevated sagittal plane movement had recovered, while the runner with decreased sagittal plane movement experienced a further drop.

At the knee, one runner decreased knee sagittal plane maximum angle beyond MDC post HIIT. By 24-h post, four runners experienced a change beyond MDC; for one runner it was a reduced angle, and the remaining three experienced increased knee flexion. Four runners displayed a reduced sagittal plane knee RoM immediately post HIIT that exceeded MDC. However, at the 24-h post, six runners exceeded MDC, with two changing from a decreased to increased RoM above MDC, while the others maintained their decreased RoM. No runner

TABLE 2 | Hip strength measures, body mass-normalised ($kg.kg^{-1}$) represented as mean ± standard deviation for pre, post, and 24-h training run along with effect size (ES; Cohen's *d*) and individuals exceeding minimum detectable change (MDC) for each variable at post and 24-h post compared to pre.

	Mean ± SD (ES)					
Strength measures	**Pre**	**Post**	**24-h**	**Time**	**Pre vs. post MDC**	**Pre vs. 24-h MDC**
Hip abduction	0.500 ± 0.16	0.444 ± 0.15*** (d = 0.36)	0.452 ± 0.15*** (d = 0.30)	†	2	3
Hip adduction	0.408 ± 0.40	0.277 ± 0.10*** (d = 0.45)	0.289 ± 0.09* (d = 0.41)		0	0
Hip flexion	0.438 ± 0.13	0.388 ± 0.12*** (d = 0.39)	0.398 ± 0.14 (d = 0.29)	†	0	0
Hip internal Rotation	0.195 ± 0.06	0.174 ± 0.06*** (d = 0.35)	0.176 ± 0.05* (d = 0.34)	†	3	4
Hip External Rotation	0.219 ± 0.06	0.191 ± 0.05*** (d = 0.51)	0.208 ± 0.06 (d = 0.18)	†	2	2

Effect size in comparison with baseline.
*† denotes significant effect with time. Significant differences in comparison with baseline indicated by *$P < 0.05$, ***$P < 0.001$.*

TABLE 3 | Neuromuscular function measures of maximum voluntary contraction (MVC) of the knee extensors, voluntary activation percentage (VA%), and quadriceps resting twitch potential ($Q_{tw,pot}$, N) at pre, post, and 24-h of training run represented as mean ± standard deviation along with effect size (ES; Cohen's *d*) and individuals exceeding minimum detectable change (MDC) for each variable at post and 24-h post compared to pre.

	Mean ± SD (ES)					
	Pre	**Post**	**24-h**	**Time**	**Pre vs. post MDC**	**Pre vs. 24-h MDC**
MVC (N)	487.4 ± 31.8	448.7 ± 31.9*** (d = 1.21)	471.8 ± 141.9* (d = 0.15)	†	6	5
$Q_{tw,pot}$ (N)	188.6 ± 43.9	162.9 ± 48.5* (d = 0.56)	183.1 ± 49.3 (d = 0.11)	†	8	2
VA%	93.2 ± 4.4	86.4 ± 7.8*** (d = 1.07)	91.3 ± 5.8* (d = 0.37)	†	15	4

Effect size in comparison with baseline.
*† denotes significant effect with time. Significant differences in comparison with baseline indicated by *$P < 0.05$ and ***$P < 0.001$.*

experienced a change above MDC for maximum angle of the knee in the frontal plane immediately post HIIT, and only one runner changed above MDC at 24-h post. This runner altered their gait strategy from running in abduction immediately post HIIT to adduction at 24-h post. For knee RoM angle, only one runner exceeded MDC immediately post HIIT with an increased RoM angle that was still present 24-h later.

Coordination Variability

Null Hypothesis Testing

Running coordination variability, assessed by vector coding coupling angle, revealed no significant change with time (see **Table 5**). Continuous relative phase variability revealed a significant change ($P < 0.05$) with time for all coupling interactions. *Post hoc* analysis showed that the increased variability observed, both immediately post and 24-h post HIIT, were significant for all examined interactions (**Table 4**).

Minimum Detectable Change

For CAV, the individual assessment showed that in $Hip_{flex/ext-}Knee_{abd/add}$ 16 runners exhibited a change above MDC immediately post HIIT. Of those 16 runners, seven had increased variability immediately post HIIT, changing to decreased variability 24-h post. The remaining nine runners exhibited decreased variability immediately post; at 24-h post, one had recovered, the rest remained fatigued. Two runners exhibited an increase in variability above MDC both immediate post and 24-h post for $Hip_{flex/ext-}Knee_{flex/ext}$ coupling. Seven runners experienced an increase above MDC change for coupling of $Hip_{abd/add}$-$Knee_{flex/ext}$ immediately post and 24-h post; three showed increased variability immediately post and two failed to recover at 24-h post. Immediately post HIIT, 14 runners increased variability above MDC in $Hip_{abd/add}$-$Knee_{abd/add}$ coupling, eight of whom failed to recover at 24-h post.

Individual assessment of $Hip_{flex/ext-}Knee_{flex/ext}$ showed that three runners experienced a change above MDC immediately post and while the three remained increased, an additional three runners exhibited increased variability at 24-h post. In $Hip_{flex/ext-}Knee_{abd/add}$, three runners increased CAV above MDC both immediately post HIIT and 24-h post. Four further runners showed increased variability 24-h post. For $Hip_{abd/add}$-$Knee_{abd/add}$, five runners exceeded MDC immediately post;

TABLE 4 | Hip and knee joint kinematics of maximal angles and range of motion (RoM) angles in the sagittal and frontal plane movements of standard pace run represented as mean ± standard deviation for pre, post, and 24-h post training run along with effect size (ES; Cohen's *d*) and individuals exceeding minimum detectable change (MDC) for each variable at post and 24-h post compared to pre.

		Mean ± SD (ES)					
		Pre	**Post**	**24-h**	**Time**	**Pre vs. post MDC**	**Pre vs. 24-h MDC**
Maximum angles (deg)							
	Hip sagittal	38.8 ± 6.2	38.2 ± 7.2 (d = 0.09)	37.4° ± 5.8 (d = 0.23)		2	3
	Hip frontal	9.6 ± 3.9	13.3 ± 4.2*** (d = 0.91)	12.7° ± 3.3*** (d = 0.86)	†	11	9
	Knee sagittal	42.9 ± 14.7	42.9 ± 6.5 (d = 0.26)	43.7° ± 4.7 (d = 0.20)		1	4
	Knee frontal	0.3 ± 4.3	–0.1 ± 3.3 (d = 0.08)	2.2° ± 4.0 (d = 0.46)	†	0	1
ROM angles (deg)							
	Hip sagittal	43.5 ± 6.5	44.6 ± 5.5 (d = 0.18)	43.8° ± 4.8 (d = 0.05)		3	1
	Hip frontal	11.9 ± 3.2	14.9 ± 3.8*** (d = 0.85)	14.5° ± 3.8*** (d = 0.74)	†	7	3
	Knee sagittal	31.3 ± 13.4	27.6 ± 4.3 (d = 0.38)	29.5° ± 5.1 (d = 0.17)	†	4	6
	Knee frontal	5.5 ± 2.6	4.8 ± 1.7 (d = 0.32)	5.3° ± 2.7 (d = 0.08)		1	1

Sagittal plane positive values represent flexion; negative values represent extension.
Frontal plane positive values represent adduction angles; negative value represent abduction movement.
Effect size is comparison with baseline.
*†denotes significant effect with time. Significant differences in comparison with baseline indicated by ***$P < 0.001$.*

all but one still exceeded MDC 24-h later. For $Hip_{abd/add}$-$Knee_{flex/ext}$ coupling, five runners exceeded MDC immediately post, and four remained elevated 24-h post. In all CRPV interactions, the runners had increased variability apart from one runner who reduced variability in all couplings except $Hip_{abd/add}$ – $Knee_{flex/ext}$.

DISCUSSION

This study found reduced hip and knee strength, increased frontal plane hip kinematics, and increased coordination variability following a HIIT session. In addition, this study is the first to not only report impairments to central and peripheral drive following a HIIT session but also that not all runners had recovered 24 h later. Null hypothesis significance testing showed fatigue-induced changes at a group level. The minimal detectable change was used to identify "real changes" at an individual level, revealing some conflicting, but mostly more variable and nuanced, findings.

Gait and Hip Strength

The HIIT induced a statistically significant decline in strength for all hip strength tests immediately post, while inducing changes to hip frontal kinematics. Additionally, runners remained in a state of reduced strength ($P < 0.05$) the following day for hip abduction, adduction, and internal rotation. Similarly, hip frontal plane kinematics were also increased at 24-h. When analysing the data using MDC rather than NHST, a far more nuanced picture emerged, with very few runners having a drop in force production. Furthermore, not all runners experienced gait changes.

Individually, 11 runners showed fatigue-induced increases in maximum hip adduction angle immediately post HIIT, evidenced by exceeded MDC. Of these 11 runners, nine failed to recover, still exhibiting an increased hip adduction angle 24-h later. Furthermore, two of the 11 runners also exhibited a loss of strength in their hip abductors beyond MDC post HIIT. At 24-h post, three runners exceeded MDC in hip abduction strength; they also showed increased maximum hip frontal angle and RoM.

These findings are also supported by previous studies examining hip abductor strength pre and post prolonged runs (Dierks et al., 2008; Bazett-Jones et al., 2013; Riazati et al., 2020), where hip abductor strength was lower following a run along with increased hip adduction angle. The findings of this study further support the suggestion of Riazati et al. (2019) that the identification of potential risk factors for developing running related overuse injuries is better performed on an individual basis.

The causality of these alterations in running gait (e.g., the observed increase in hip adduction angle), has been mostly attributed to muscular decrements (Dierks et al., 2008; Noehren et al., 2014). Runners suffering from patellofemoral pain and iliotibial band syndrome exhibit dysfunction at the gluteus medius muscle, which can result in poor frontal plane movement control (Semciw et al., 2016). While muscle activity was not measured, a reduction in gluteus medius force production

TABLE 5 | Joint coupling interactions of sagittal and frontal plane movements of the hip and knee measured through vector coding coupling angle variability (CAV) and continuous relative phase variability (CRPV) during SPR runs at pre, post, and 24-h post training run represented as mean ± standard deviation along with effect size (ES; Cohen's *d*) and minimum detectable change (MDC) for each variable at post and 24-h post compared to pre.

	Mean ± SD (ES)					
	Pre	**Post**	**24-h**	**Time**	**Pre vs. post MDC**	**Pre vs. 24-h MDC**
CAV (deg)						
$Hip_{flex/ext}$- $Knee_{flex/ext}$	66.7 ± 5.3	67.3 ± 4.9 (d = 0.12)	66.2 ± 4.5 (d = 0.10)		2	2
$Hip_{flex/ext}$-$Knee_{abd/add}$	66.8 ± 6.3	67.3 ± 5.2 (d = 0.09)	68.0 ± 4.6 (d = 0.22)		16	15
$Hip_{abd/addt}$-$Knee_{flex/ext}$	71.7 ± 1.8	71.4 ± 2.5 (d = 0.14)	71.6 ± 2.2 (d = 0.05)		7	7
$Hip_{abd/addt}$-$Knee_{abd/add}$	68.4 ± 4.8	68.6 ± 4.2 (d = 0.44)	69.8 ± 3.3 (d = 0.34)		14	8
CRPV (deg)						
$Hip_{flex/ext}$- $Knee_{flex/ext}$	12.9 ± 3.9	17.8 ± 10.1* (d = 0.64)	19.7 ± 13.0* (d = 0.74)	†	3	6
$Hip_{flex/ext}$-$Knee_{abd/add}$	9.1 ± 4.8	15.2 ± 14.1* (d = 0.56)	20.3 ± 16.5* (d = 0.90)	†	3	7
$Hip_{abd/addt}$-$Knee_{flex/ext}$	16.2 ± 4.1	23.5 ± 13.9* (d = 0.73)	26.0 ± 12.6** (d = 1.05)	†	5	4
$Hip_{abd/addt}$-$Knee_{abd/add}$	11.0 ± 4.9	21.3 ± 14.3** (d = 0.93)	23.3 ± 14.7** (d = 1.10)	†	6	9

Effect size is comparison with baseline.
*† denotes significant effect with time. Significant differences in comparison with baseline indicated by *P < 0.05, **P < 0.01.*

observed through decreased hip abduction strength is the likely cause for the increased hip adduction angles. The inability to control hip frontal movement can also contribute to increased strain on the IT band and stress on the patellofemoral joint (Noehren et al., 2007; Dierks et al., 2010; Powers, 2010). The findings of this study provide further support to the previous body of evidence suggesting reduced force production to be the cause of altered frontal kinematics (Dierks et al., 2010; Powers, 2010; Brown et al., 2016; Willwacher et al., 2020).

Neuromuscular Function

The HIIT session induced decrements to both central and peripheral neuromuscular function immediately post, with reductions of 6.8% in VA, 8.1% in MVC, and 14% in $Q_{tw,pot}$. Post 24-h, the runners remained in an impaired state ($P<0.05$) despite recovering to a reduction of 2.0% in VA, 3.2% in MVC, and 3.0% in $Q_{tw,pot}$. The impairments immediately post were lower than those previously found. Following maximal repeated sprints Goodall et al. (2014) reported a drop of 12% in KE MVC and 23% in $Q_{tw,pot}$. Similarly, Ross et al. (2010) observed a 15% in KE MVC and a 13% drop in VA following a 20-km run. The reduction in $Q_{tw,pot}$, however, is slightly higher than runs of 1 h (13%) or 30 km (8%) reported by Davies and White (1982) and Millet et al. (2003), respectively. The decrement of VA in this study was lower than the previously reported reductions following an ultramarathon (13%), 24-h treadmill running (33%), and repeated sprints (9%) (Millet et al., 2002; Martin et al., 2010; Goodall et al., 2014). This observation, as a group, was however not unexpected as the mechanisms and extent of fatigue are exercise domain dependent. Fatigue resulting from prolonged activity in the moderate domain has been shown to be mostly of central origin (Burnley and Jones, 2016) while the HIIT was in the severe domain, inducing both central and peripheral decrements.

This study is the first to report individual impairments in neuromuscular function immediately and 24-h post HIIT. Sixteen of the 20 participants showed decrements in neuromuscular function, with four showing a loss of performance in all three measures. Peripheral fatigue was evident with decrements in the contractile function of the knee extensors. There was an impaired force output, measured through $Q_{tw,pot}$, immediately post HIIT that persisted for 24-h ($P < 0.05$). Such a decrement in force output could be due to both metabolic and/or mechanical factors that influence excitation-contraction coupling along with action potential transmission at the sarcolemma (Allen et al., 2008). The reduced $Q_{tw,pot}$ is an indicator of a reduction in the excitation-contraction coupling process. This could be at the cross-bridge level resulting from metabolic and mechanical disturbances, as well as impairments to neuromuscular transmission at the sarcolemma (Allen et al., 2008; Goodall et al., 2014). Moreover, it could be due to mechanical stresses e.g., a disorganisation of sarcomeres and Ca^{2+} handling interference (Skurvydas et al., 2016).

Central fatigue was evident immediately following HIIT with a large drop (ES = 1.06) in VA ($P < 0.05$) that was experienced by 15 participants, four of whom had failed to recover 24-h later. It is not possible to identify the supraspinal mechanisms that resulted in the central fatigue in this study, only that there was fatigue "upstream" of the peripheral nerve. A reduction in central drive while decreasing motor unit recruitment, from either firing frequency and/ or the number of motor units recruited, contributed to the decline in MVC (Gandevia, 2001). The HIIT session was performed in the severe domain, resulting in the accumulation of metabolites in the extracellular fluid e.g., H^{+}, Pi, K^{+} which can stimulate type III and IV afferents reducing central drive (Amann, 2011). Central factors might therefore be responsible for some of the changes in coordination variability. Changes in gait variability could be seen as a "loss of control" rather than due solely to peripheral fatigue.

Coordination Variability

By the end of the HIIT the runners were unable to maintain a stable level of coordination measured by CRPV ($P < 0.5$), this was still evident 24-h later. With CAV, there was no group effect, however, several runners exhibited an increase beyond MDC. Increased variability could be the result of decrements in force production and/or impairments in neuromuscular control having central and/or peripheral origins, as observed in this study. The detection of fatigue through variability could signal decrements in the contractile or neural function of the muscles when not examined directly. Each of the four runners who experienced an impairment to either central or peripheral drive at 24-h post concurrently had increased coordination variability in at least one coupling for either CAV or CRPV. The persistence of increased coordination variability at the 24-h post would suggest that the contractile and/or neural decrements might not have recovered. It is possible that if reduced variability can be used as a tool to discriminate between injured and non-injured runners (Seay et al., 2011), increased variability could provide a means to detect fatigue.

Schöner (1995) suggested that muscles and joints can be organised by the central nervous system to stabilise different task-specific performances. Instability can be identified as when motor systems, or processes that modulate coordinated movements, are unable to return to a certain state following small perturbations (Latash and Huang, 2015). Changes, both increases and decreases, in coordination variability by the end of the HIIT session show that two joint coordination instability had increased. These changes in coordination variability and gait (in)stability could be due to decrements in central nervous system function, with neurological patients exhibiting atypical, multi-joint coordination movement patterns. This can lead to compensatory changes in muscle activation strategies, for example an increased co-activation of agonist-antagonist muscle to impact gait deviation, thereby decreasing variability to improve stabilisation (Latash and Huang, 2015). By the end of the HIIT session, most runners were unable to maintain a stable running form. This was probably caused, in part, by impaired central drive, along with reduced capability of the gluteus medius muscle, working eccentrically, to act as a brake, resulting in increased variability.

Bartlett (2004) suggested that little or no variation in a movement would result in the same tissue being loaded at each ground contact, with potentially damaging consequences. Ferber and Pohl (2011) observed increased variability, albeit in walking, following locally induced fatigue in healthy participants. They attributed this to the diminished ability of the posterior tibialis to produce force, therefore requiring greater assistance from other muscles that contribute to the same joint movement in providing stability. Given the increase in hip abduction angle and reduction in hip abductor force production during the HIIT, the runners could have required a compensatory increase in the activation of other muscles contributing to this movement (e.g., gluteus minimus and tensor fascia lata) (Flack et al., 2014). Additionally, the decrease in muscle force could suggest a decreased recruitment which could explain the increase in hip adduction RoM. Increased coordination variability could, therefore, be considered as a mechanism to distribute impact loading as the muscle becomes fatigued. This requires further examination through direct measurement of muscle activity using electromyography. Furthermore, studies using wearable technology or a markerless motion capture system could enable this to be tested outside of a lab where more ecologically valid testing can be performed on large samples.

Statistical Approaches

Two different statistical approaches were used within this paper: conventional null-hypothesis statistical tests and the detection of a "real change" using MDC. These approaches, at times, gave contrasting findings, while at other times showed agreement. Hip adduction strength is a good example, whereby a statistically significant reduction was seen immediately post HIIT ($P < 0.001$) which failed to recover by 24-h post ($P < 0.05$), whereas no runner showed reductions that exceeded the minimum detectable change. The approach adopted, therefore, dramatically altered the conclusion drawn. In this instance, in our opinion, the small to modest effect sizes support the conclusion drawn from using MDC. By contrast coordination variability of $hip_{flex/ext}$ – $knee_{abd/add}$, showed no significant difference at any point post HIIT, however this masked the considerable inter-individual responses. Immediately post-HIIT 16 of the 20 runners had changes in variability in excess of MDC, with seven increasing and nine decreasing, highlighting inter-individual variation. These inter-individual variations could explain the lack of statistical significance. After 24 h, all seven runners who had demonstrated increased variability, now showed a reduced variability (i.e., greater than MDC). Of the nine runners with reduced variability immediately post-HIIT, one recovered (i.e., fell back within MDC) and the rest continued to show reduced variability. Minimum detectable change offers the potential to detect more nuanced, individual strategies that might otherwise be overlooked.

Implications

An increase in hip adduction angle has been considered to be a risk factor for the development of patellofemoral pain (Noehren et al., 2013). In this study, the MDC for hip adduction angle was 5.0°, beyond this we considered a runner to be at increased risk. Just over half of the runners in this study, exhibited a real change with an increase in hip adduction immediately post HIIT, only two of whom had recovered 24-later. This suggests that these runners could potentially start their next training session with an elevated risk of developing patellofemoral pain.

If runners recover from the fatigue, which most in this study did, then there is unlikely to be a risk of injury development. As runners often train on consecutive days, a lack of adequate recovery could lead to potential overuse injury development (Bertelsen et al., 2017). At 24-h post, all but four runners had recovered from impairments to both VA and $Q_{tw,pot}$. This is not surprising as the vast majority of runners do not experience an injury after each training run, matching epidemiological data identifying 7.7 injuries every 1,000 h of running in recreational runners (Videbaek et al., 2015). This study highlights an appropriate method to identify the few runners who are at an increased risk of injury.

The use of MDC suggests increased injury risk is individual and that not only did each runner differ in risk at the end of the session but also with recovery pattern. The findings of this study further support the suggestion of Riazati et al. (2020), that assessing the potential risk of developing running related overuse injuries is better performed on an individual basis. Individual variations in the extent and origin of fatigue, along with recovery, further support the use of alternative statistical approaches to examine fatigue effects on runners.

CONCLUSION

Following a HIIT session, middle-aged recreational club runners, experienced statistically significant impairments to both central and peripheral drive, along with changes in gait kinematics, gait variability, and a reduced ability to produce force at the hip and knee. Identifying individuals who changed by more than the minimum detectable change revealed considerable inter-individual variation and a more nuanced picture. The majority of runners showed a reduction in central drive and an increase in gait variability by the end of the HIIT session, reflecting a possible loss of motor control. Most of these runners were able to recover within 24-h, however, a small number failed to do so, and still had decrements in neuromuscular function, muscle force production, altered kinematics, and coordination variability. For these runners, running again before they have fully recovered could pose an increased risk of succumbing to an overuse injury.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Northumbria University. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SR, PH, and NC contributed to the conception/design of the work along with interpretation of the data. MM contributed to the data analysis. All authors drafted the intellectual content and the final version.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fspor.2022.830278/full#supplementary-material

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