Sport-specific use of doping substances: analysis of World Anti-Doping Agency doping control tests between 2014 and 2017

Running Head: Prohibited substances across Olympic sports

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Abstract

Background: In recent years, there has been a solid effort across all sports organisations to reduce the prevalence and incidence of doping in sport. However, the efficacy of current strategies to fight against doping might be improved by using anti-doping polices tailored to the features of doping in each sport. *Objectives:* The aim of this investigation was to analyse the substances more commonly found in doping control tests in individual and team sports. *Material and Methods:* The publicly accessible Testing Figures Reports made available by the World Anti-Doping Agency, were analysed from 2014 to 2017. *Results:* The most commonly detected groups of banned substances were anabolic agents and stimulants but the distribution of adverse findings per drug class was very different depending on the sports discipline. Weightlifting, athletics, rugby, hockey and volleyball presented abnormally high proportions of anabolic agents ($p=2.8\times10^{-11}$). Cycling, athletics and rugby presented atypically elevated proportions of peptide hormones and growth factors ($p=1.4x10^{-1}$). Diuretics and masking agents were more commonly found in boxing, wrestling, taekwondo, judo, shooting, and gymnastics than in other sports ($p=4.0\times10^{-68}$). Cycling, rowing, aquatics, tennis, gymnastics and ice hockey presented abnormally high proportions of stimulants ($p=1.8.x10^{-5}$). *Conclusions:* These results indicate that the groups of banned substances more commonly detected in anti-doping control tests were different depending on the sports discipline. These data suggest the prohibited substances used as doping agents might be substantially different depending on the type of sport and thus, sports-specific anti-doping policies should be implemented to enhance the efficacy of anti-doping testing.

Keywords: elite athlete, sports performance, banned drugs, anti-doping, competition.

Introduction

Doping in sport is a well-studied phenomenon from both medical and psychosocial perspectives (Pielke, 2018), and one of the most recurrent conclusions is that doping might vary greatly depending on the type of sport, sports level, and athletes' attitudes and beliefs, with other contributors from the context surrounding the athlete that also affects doping misconduct (Morente-Sánchez & Zabala, 2013). However, current knowledge about doping practices has not always been effectively translated to the fight against doping.

After years of apparent disorganisation in the fight against doping, the World Anti-Doping Agency (WADA) was conceived to harmonise anti-doping policies worldwide and to equilibrate the pressure of the fight against doping among sports. In this respect, one of the most important achievements against doping has been the implementation of a homogeneous set of anti-doping rules, such as the World Anti-Doping Code (World Anti-Doping Agency, 2015). The Code has provided the framework for coordinated policies, rules and regulations among sports organisations and public authorities (Lippi, Franchini, & Guidi, 2008). The Code has also allowed the publication of an annually updated Prohibited List of Substances and Methods that is the same for all sports, with only particular exceptions (Handelsman, 2015). While these strategies might be compelling to avoid the emphasis of anti-doping on particular sports, or athletes, this approach perhaps precludes the use of more rationalised methods to fight against doping. It is likely that sports-specific anti-doping rules, based on the most typical doping misconduct in each sport, might be essential for developing more preventive and dissuasive anti-doping programmes.

Adopting anti-doping policies that consider doping as a phenomenon strongly tailored by the characteristics of each sport might be more effective to accommodate the differences in cheating misbehaviour among sports disciplines. This approach should then consider what prohibited substances and methods are more commonly used or found in each sport to increase the pressure to specifically pursue them in anti-doping control testing. One recent example is the prohibition of tramadol, adopted only by the *Union Cycliste Internationale* (Union Cyclste Internationale, 2019) in response to the high use of this opioid mainly in road cycling (Baltazar-Martins, Plata, et al., 2019; Baltazar-Martins et al., 2019). Other evidence also suggests the convenience of sports-specific anti-doping protocols, such as the uneven incidence of doping across Olympic sports (Aguilar-Navarro, Muñoz-Guerra, Plata, & Del Coso, 2019), showing that doping is not a homogeneous phenomenon in sport. Interestingly, although doping misconduct has greatly evolved in recent years, the sports with the highest proportion of substances found in doping control samples have remained relatively the same since the creation of WADA (Aguilar-Navarro et al., 2019).

In an attempt to perform more intelligent and effective anti-doping testing, WADA has released a technical document for sports specific analysis (TDSSA), intended to ensure a consistent minimum level of analysis of particular prohibited substances within certain sports (World Anti-Doping Agency, 2019b). In addition, WADA has launched an International Standard in Testing and Investigation aimed to assess the risk of which prohibited substances and/or methods are most likely to be abused in particular sports (World Anti-Doping Agency, 2019a). Although this is a big step towards sports-specific anti-doping testing, these document sets a minimum level of measurement for only a few substances, and it is not soundly based on scientific reports that confirm the substances more commonly found in each sport --probably because the evidence is scarce--. In fact, the load of deciding what substances should be pursued in the distribution plans in each sport is imposed on anti-doping organizations which likely have less resources to assess doping trends in each sport. Thus, the aim of the current investigation was to analyse the number and distribution of adverse analytical findings per drug class in individual and team sports using data from doping control testing.

Materials and Methods

The present study is an analysis of the Testing Figures Reports made available annually by WADA. These Reports include information from WADA-accredited laboratories regarding the number of samples analysed and the number of adverse findings per drug class. As per definition of the World Anti-Doping Code, and adverse analytical finding was defined as a report from a WADA-accredited laboratory or other WADA approved laboratory that identifies in a sample obtained in a doping control test the presence of a prohibited substance or its metabolites or markers. The evidence of the use of a prohibited method was also considered as an adverse analytical finding. Although WADA has been publishing the Testing Figures Report since 2003, information about the adverse analytical findings per drug class in each sport was only included for the first time in the Report of 2014. Thus, the information to establish the banned substances more commonly found in each sport is only available in the last four Reports (2014, 2015, 2016 and 2017) and this investigation represents an analysis from 2014 to 2017.

In these Reports, the adverse findings are categorised following the group of substances included in the List of Banned substances (World Anti-Doping Agency, 2019c) as follows: anabolic agents, peptide hormones and growth factors, β-2 agonists, hormone and metabolic modulators, and diuretics and masking agents, prohibited at all times (i.e., in- and out-of-competition); stimulants, narcotics, cannabinoids, and glucocorticoids, prohibited only in-competition; and β-blockers, prohibited in-competition in particular sports such as shooting and skiing.

The current investigation presents an *ad hoc* analysis of adverse analytical findings per drug class in 18 individual sports (Aquatics, Athletics, Biathlon, Boxing, Canoe/Kayaking, Cycling, Fencing, Gymnastics, Judo, Rowing, Shooting, Skating, Skiing, Taekwondo, Tennis, Triathlon, Weightlifting and Wrestling) and 7 team sports (Basketball, Football, Handball, Hockey, Ice Hockey, Rugby and Volleyball). As it was impossible to analyse all the sports included in the WADA Testing Figures Reports, the above-mentioned individual and team sports were selected because they accounted for at least 1,400 samples per year in all the years examined. This cut-off was selected to guarantee that the distribution of adverse findings per drug class was representative of each sport. In addition, the use of the aggregated data of the 4 available Reports made it possible to increase the statistical power of the analysis. Of note, only complex team sports were labelled as a "team sport", while other individual disciplines with some collective events (such as athletics, swimming, cycling, rowing, etc) remained labelled as an "individual sport" because most of the samples analysed came from the individual events. This analysis has followed a similar pattern to a previous publication in which the differences in the frequency of adverse analytical and atypical findings among sports was assessed (Aguilar-Navarro et al., 2019).

Statistical analysis

The data were electronically extracted from the Testing Figures Reports and entered into a database designed for the purposes of this research. The data were extracted by one author (MAN) using a spreadsheet (Excel 2016, Microsoft Office, WA, USA) and then they were checked for accuracy by another author (JDC). Then, mean and standard deviation (SD) were obtained for the number of samples analysed, the number of adverse analytical findings and the number of adverse and analytical findings per drug class from the total of the years investigated (2014-2017). Afterwards, the proportion of adverse analytical findings in each sport was calculated annually by dividing the number of adverse analytical findings by the number of samples. The proportion of analytical findings per drug class in each sport was calculated by dividing the number of adverse findings in each drug category by the total number of adverse findings.

A one-way analysis of variance was used to detect differences in the frequency of adverse findings among sports. The Games-Howell *post-hoc* analysis was then employed to identify differences among sports in this variable. The differences in distribution of the adverse analytical findings per drug class were tested with crosstabs and Chi Square tests, including adjusted standardised residuals. Briefly, it was considered that a sport had a distribution of adverse findings per drug class statistically different from expected when its distribution of findings among all the drug categories was > or< the critical value of Z (i.e., 1.96). The data were analysed with the statistical package SPSS v 20.0 (SPSS Inc., Chicago, IL). The significance level was set at $p<0.05$ (i.e., $p<5.0\times10^{-2}$).

Results

A total of 513,157 samples were analysed from the individual sports selected for this investigation from 2014 to 2017. Table 1 contains information about the number of samples analysed per year in each sport presented as mean ± SD. Overall, the frequency of adverse analytical findings in individual sports was 1.0 ± 0.6%, although there were substantial differences in the proportion of adverse findings among sports (Figure 1). Weightlifting, boxing and wrestling were the sports with the highest proportion of adverse analytical findings ($p<5.0\times10^{-2}$) with the remaining sports showing a proportion of adverse findings lower than 2% in their samples for all the years analysed. A detailed analysis of the number of adverse findings in each sport is included in Table 1. However, to allow a better comparison of the banned substances more commonly found in each sport, the lower panel of Figure 1 contains the distribution of the adverse findings in each sport per drug category. Table 3 contains information to identify if the distribution of findings per drug category in each sport was different from the "expected" distribution.

The proportion of anabolic agents found in weightlifting and athletics was higher than expected (Table 3; (p<5.0×10^{-2}). Peptide hormones and growth factors were more commonly found in cycling and athletics when compared to the distribution of the remaining sports (p=2.9×10^{-47}). Cycling, triathlon and aquatics had a higher proportion of β2-agonists (p=3.3×10^{-24}), while wrestling, athletics, canoe/kayaking, biathlon, and skating presented higher than expected frequencies in hormone and metabolic modulators (p=6.1×10^{-54}). Interestingly, diuretics and masking agents were more commonly found in boxing, wrestling, taekwondo, judo, shooting, rowing and gymnastics (p=4.0×10^{-68}). The proportion of stimulants in cycling, rowing, aquatics, tennis, and gymnastics was higher than expected from the overall distribution present in the remaining sports (p=2.3×10^{-37}). The proportion of narcotics was higher in cycling (p=8.6×10^{-3}), cannabinoids were abnormally present in the samples of boxers, tennis players, and fencers (p=5.2×10^{-12}), glucocorticoids were higher in cycling, triathlon, and skiing and β-blockers were only found in shooting (Table 3).

In team sports, the number of samples analysed was 239,367 while the number of samples analysed per year in each team sport can be found in Table 2. The overall frequency of adverse analytical findings in team sports was of 0.8 ± 0.3%, although, as in individual disciplines, there were substantial variations in the frequency of adverse findings among team sports (Figure 2). Rugby, ice hockey and basketball are the three sports presenting the highest proportion of adverse findings although from a statistical point of view only rugby showed a significant difference with respect to volleyball and football ($p<5.0\times10^{-2}$). As depicted in the lower panel of Figure 2 and Table 4, the frequency of anabolic agents was higher than expected in rugby, hockey and volleyball ($p=2.8\times10^{-11}$). Peptide hormones and growth factors were more commonly found in rugby ($p=1.4\times10^{-1}$), β2-agonists in ice hockey and handball ($p=1.2\times10^{-6}$), and stimulants in ice hockey ($p=1.84\times10^{-5}$). The frequency of narcotics was higher in rugby and handball ($p=1.5\times10^{-4}$), cannabinoids in basketball ($p=3.7\times10^{-9}$) and glucocorticoids in football ($p=8.0\times10^{-7}$).

Discussion

Due to the paucity of data regarding the most consumed banned substances in each sports discipline, the aim of the current investigation was to analyse the number and distribution of adverse analytical findings per drug class in individual and team sports. With this goal in mind, we used the data provided by the WADA Testing Figures Reports from 2014, the moment at which, for the first time, the adverse analytical findings in each sport were categorised per drug class. The main outcomes of this investigation reflect an uneven distribution in the percentage of adverse findings and the distribution of these findings per drug category across all sports (Figures 1 and 2). Overall, this investigation indicates that the banned substances more commonly detected in anti-doping control tests were different depending on the sports discipline, which suggests that doping might be a phenomenon with unique characteristics in each sport.

From a simplistic point of view, physical performance in most sports might be defined as the combination of four major components: skill, strength, endurance and recovery (Handelsman, 2015). In the market, there are drugs that have the capacity of improving these four dimensions and thus, the use of banned substances in each sport might be dictated by these dimensions of sports performance. For instance, as proposed previously (Handelsman, 2015), sports requiring maximal force and explosive power are most susceptible to androgen doping through their effect on increasing muscle mass and strength. Sports requiring aerobic endurance capacity are likely most susceptible to blood doping or other strategies to artificially increase the blood's oxygen carrying capacity to exercising muscle. Contact sports and those involving intense physical activity or training may also be enhanced by growth hormone and glucocorticoids because of their effect on enhancing tissue recovery from injury. Finally, sports that are influenced by skill and concentration may benefit from drugs that reduce anxiety, tremor, inattention or fatigue. The proposal raised by Handelsman (2015) is an interesting theorical approach to the differences in the banned substances more commonly used in each sport, and it is partially supported by the facts presented in this investigation.

As previously found (Aguilar, Muñoz-Guerra, Plata, & Del Coso, 2017), anabolic agents are the most common banned substances detected when accounting for all individual and team sports, with the remaining groups of substances being found much less frequently. However, the novelty of this investigation is that it pinpoints which sports had a higher number and proportion of adverse findings related to anabolic agents (Table 1, 2, 3 and 4). In this respect, weightlifting, canoeing, and athletics —individual sports— and rugby, hockey and volleyball —team sports— were the ones in which the percentage of anabolic agents in adverse doping control tests was higher than expected, compared to the remaining sports. Despite the differences in the competition rules of these sports, all of them are characterised by the necessity of maximal force/power production. In addition, in these sports, the athlete's body mass/muscle mass/girth are not detrimental for success. Interestingly, a high rating of adverse findings by anabolic agents is not present in other strength- and power-based sports where an increase in body mass reduces performance (i.e., gymnastics) or implies a change of category (i.e., boxing, wrestling, taekwondo, etc). Thus, the implementation of the steroidal module of the Athlete Biological Passport might be of little value in these particular sports.

On the other hand, growth factors and peptide hormones were more commonly found in cycling, athletics, and rugby. In the list of banned substances (World Anti-Doping Agency, 2019c), the group of growth factors and peptide hormones mainly contains drugs with the potential of increasing the blood-oxygen carrying capacity, such as erythropoietins and hypoxia-inducible-factor activating agents. Thus, it might be fairly speculated that athletes of these three sports might be more prone to using artificial manipulations of the blood, coinciding with previous data obtained by questionnaire (Alaranta et al., 2006). This might be especially applicable to cycling and athletics because they had > 30 adverse findings per year in this category of substances (with only ~2 findings per year in rugby; Table 1 and 2). Conversely, the presence of adverse findings due to growth factors and peptide hormones in other sports such as shooting, gymnastics, fencing and most team sports was negligible which suggests that the doping controls to search for this class of drugs might be avoided in several disciplines.

Cycling, triathlon and aquatics —individual sports—, and ice hockey and handball —team sports— had an unusually high proportion of β2-agonists in the doping control tests than the remaining sports. Although β2-agonists are substances prohibited in- and out-of-competition, WADA currently allows the therapeutic use of salbutamol, formoterol and salmeterol and these substances are only considered as an adverse finding when they surpass a threshold (World Anti-Doping Agency, 2019c). Furthermore, ~4% of athletes request a Therapeutic Use Exemption (TUE) for other β2-agonists, such as terbutaline, because they have objectively demonstrated that they suffer from asthma or exercise-induced bronchoconstriction (Anderson et al., 2006). Thus, it is likely that the high proportion of adverse findings due to β2-agonists in the aforementioned sports is the result of the higher number of TUEs in these particular sports. The use of medical exemptions has raised concerns because approximately 40% of all Olympic athletes suffer from asthma in certain sports disciplines (Herzog, 2017) and it has been recently suggested that the therapeutic exemption for β2-agonists should be revisited by anti-doping authorities as athletes might be using the TUEs to obtain other performance enhancing-properties of these drugs (Jacobson & Fawcett, 2016; Jacobson & Hostrup, 2017).

Higenamine is a β2-agonist commonly found in dietary supplements, particularly in those with purported effects associated to enhanced performance and body weight loss. From 2016, the urine samples containing higenamine were considered as an adverse analytical finding and some athletes have claimed since then that they were inadvertently consuming this substance through adulterated dietary supplements (Grucza et al., 2019). In fact, studies of dietary supplements conducted by the Netherlands Food and Consumer Product Safety Authority between 2013 and 2018 found that ~10% of dietary supplements under analysis were adulterated with higenamine (Biesterbos, Sijm, van Dam, & Mol, 2019). Thus, the unusually high proportion of β2-agonists in the doping control tests cycling, triathlon and aquatics might be associated to the use of supplements adulterated with higenamine, because these three sports are within the sports with the highest prevalence of dietary supplements use (Baltazar-Martins, Brito de Souza, et al., 2019).

Another interesting outcome of this investigation is the high rating of diuretics and masking agents found in sports such as boxing, wrestling, taekwondo and judo. Fasting, skipping meals, and exercise-induced dehydration protocols are common and legal methods of rapid weight loss used prior to competition in weight category sports. However, around 20% of weight-category athletes also indicate the use of diuretics or other pharmacological methods for reducing weight (Berkovich, Stark, Eliakim, Nemet, & Sinai, 2019). Although gymnastics is not a weight-category discipline, a low body mass and other anthropometric factors related to thinness might be perceived as helpful for performance and the current data indicate that the control of diuretics should also be focused on gymnasts. Of note, a high proportion of diuretics was also found in shooting, despite diuretics or other similar agents not having a clear advantage for accuracy during shots. Perhaps, diuretics might be employed to mask the use of beta-blockers in shooting (Figure 1), which has been shown in this sport (Fitch, 2012). In any case, the search for diuretics and masking agents in doping control testing should be kept in all disciplines as a low but stable level of this group of substances is found across all sports.

Overall, stimulants were the most prevalent group of substances found in the doping control tests within the group of banned substances that are prohibited only in-competition (Aguilar et al., 2017). Despite the ease with which they can be detected in the laboratory, and the proven effectiveness to increase performance of other legal stimulants such as caffeine (Aguilar-Navarro et al., 2019; Salinero, Lara, & Del Coso, 2019), the current analysis indicates that banned stimulants are still popular among athletes (Deventer, Roels, Delbeke, & Van Eenoo, 2011). Perhaps, the high frequency of supplements contaminated with prohibited stimulants such as oxilofrine and methylhexanamine (Mathews, 2018) affects the elevated number of adverse analytical findings associated to these group of substances. Particularly, the proportion of adverse findings due to stimulants was abnormally high in cycling, rowing, aquatics, tennis, and ice hockey. To our knowledge, there is no a clear explanation for the high use of stimulants in most of these disciplines -when compared to the remaining disciplines- and this might be an artefact of the statistical comparison rather than a sign of abuse in these sports. However, the motives for the high proportion of stimulants in gymnastics should be further investigated because ~56% of the total number of adverse finding in gymnasts was related to the use of a banned stimulant. Interestingly, stimulants are typically used as treatment for attention-deficit/hyperactivity disorder (ADHD) among elite athletes, which has raised concerns in last years. To this regard, it has been argued that stimulant use may be a reasonable option for school-age athletes with ADHD but no at the professional level (Reardon & Factor, 2016) while others state that banning therapeutic use of stimulants may lead to an unfair playing field for athletes with ADHD (Garner, Hansen, Baxley, & Ross, 2018). Gymnastics have a high proportion of young athletes it might be speculated that the high use of stimulants in this sport might be in part the result of the use of this type of drug as a treatment for ADHD. However, this speculation merits further investigation.

The use of cannabinoids was higher than expected in boxers, fencers and basketball and tennis players. Because there is no evidence to support the ergogenic effect of cannabinoids in sport (Kennedy, 2017), it is presumable that the high rating of cannabinoids in doping control testing of these sports is due to its popularity as a social drug. In any case, the lack of performance effect does not dispute the necessity of prohibiting cannabinoids in these and other sports due to the proven adverse effect that these drugs have on athletes (Saugy et al., 2006). Lastly, a higher effort for controlling the use of glucocorticoids might be recommended in cycling, skiing and football, because they presented an atypically high proportion of adverse findings in these sports. Although the use of glucocorticoids is in most cases to treat sports-specific injuries in these disciplines (Dvorak, Feddermann, & Grimm, 2006; Earl et al., 2014) the monitoring of this group of substances in out-of-competition samples might help to ascertain whether some athletes use them as a doping agent to increase several aspects of sports performance (Heuberger & Cohen, 2019).

Within the group of hormone and metabolic modulators, it is worth mentioning the case of meldonium, an anti-ischaemic drug that some athletes seemed to be under the wrong impression that was a stealth drug, that evaded detection. Meldonium was primarily manufactured by a Latvian drug company and the drug was registered for use throughout Eastern Europe countries. Although the scientific evidence of the performance enhancing properties of meldonium was scarce (Schobersberger, Dünnwald, Gmeiner, & Blank, 2017), in January 2016, WADA decided to include meldonium in the list of banned drugs because evidence of the abuse of this substance by athletes with intentions of increasing performance (World Anti-Doping Agency, 2016). After the inclusion of meldonium in the list of banned substances, numerous athletes were tested positive for this drug in 2016 (515 cases) and 2017 (79 cases). In our analysis, wrestling, athletics, canoe/kayaking, biathlon, and skating presented higher than expected frequencies in hormone and metabolic modulators. The Report WADA Report of adverse analytical findings does not offer information of the substances detected in each sport and we cannot certify that these sports presented more cases of meldonium in 2016 and 2017. However, it is highly likely that the abnormal frequency of hormone and metabolic modulators in these sports was somewhat related to the inclusion of meldonium in the prohibited list, particularly because meldonium represented 71% of all the adverse findings related to hormone and metabolic modulators in 2016.

The current investigation presents some limitations that should be discussed to correctly understand the outcomes of the research. First, this investigation only contains information about prohibited substances, but it lacks data on the prevalence of prohibited methods employed to increase performance, such as manipulation of blood and blood components, and chemical and physical manipulations. Further investigations should explore whether the use of prohibited methods is also affected by the characteristic of the sport. Secondly, the current investigation analyses the number of samples and adverse findings reported by WADA-accredited laboratories. However, not all the adverse findings finish in an adjudicated or sanctioned anti-doping rule violation (de Hon & van Bottenburg, 2017). This is because all adverse findings are subjected to a results management process which includes matching results with TUEs and/or longitudinal studies, which can result in no sanction. In addition, sports tribunals that evaluate doping cases occasionally determine that the athletes are not at fault even after a clear adverse finding has been reported by a WADA-accredited laboratory. Thus, the outcomes of this investigation cannot be extrapolated to infer the proportion of sanctioned doping misconducts in each sport. Finally, the analysis presented here included information of only 4 reports (from 2014 to 2017) and further reports should be used to strengthen the outcomes of this investigation.

In conclusion, the analysis of the WADA Testing Figures Reports suggests that the prohibited substances used as doping agents might be substantially different depending on the type of sport. Thus, the outcomes of this research indicate that more sports-specific anti-doping strategies should be implemented to enhance the efficacy of the current anti-doping testing protocols, following the lead already initiated with the International Standard for Testing and Investigation and the TDSSA (World Anti-Doping Agency, 2019b). Specifically, the pressure to search for anabolic agents should be increased in sports where maximal muscle strength and power are imperative for success, but in which increased body mass and muscle mass have not a negative impact on performance. Peptide hormones and growth factors should be mostly looked for in samples from endurance disciplines such as cycling and athletics, while the search for these substances might not need to be arranged in other sports such as shooting, gymnastics and fencing. The concession of TUEs for β2-agonists should be further studied in sports such as cycling, triathlon and aquatics because an atypically high proportion of β2-agonists are found in these samples. A higher anti-doping pressure in controlling the use of diuretics should be made in weight-category sports, especially on the days preceding the weigh-in for competition. The percentage of stimulants in adverse findings was moderate-to-high in most sports disciplines and thus, anti-doping control testing for this group of banned substances should be transversal in all sports; however, special attention to control the use of stimulants should be imposed in gymnastics. Finally, greater scientific attention to ascertain the motives for using glucocorticoids should be paid in cycling, skiing and football. These sports-specific anti-doping policies might be helpful to enhance the efficacy of the anti-doping testing and make elite sport fairer.

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List of abbreviations

TDSSA, Technical Document for Sports Specific Analysis

TUE, Therapeutic Use Exemption

WADA, World Anti-Doping Agency

Availability of data and supporting materials section

All the data used in this investigation are publicly available at the WADA official website. https://www.wada-ama.org/en/resources/laboratories/anti-doping-testing-figures-report

Disclosure statement

The authors declare that they have no competing interests.

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Table 1. Number of samples and number of adverse analytical findings in individual sports according to the categories of banned substances proposed by WADA.

Individual sports	Samples	Anabolic agents	Growth factors	β2-agonists	Hormones	Diuretics	Stimulants	Narcotics	Cannabinoids	Glucocorticoids
Weightlifting	9618±930	163.0±67.3	4.3±2.9	4.3±3.5	19.8±14.9	21.5±9.0	20.3±3.8	0.8±0.9	1.8±0.5	4.8±2.2
Boxing	4476±392	30.8±9.5	0.8±0.5	5.0±1.2	10.0±9.9	24.0±5.2	12.8±4.2	1.0±1.4	5.0±2.9	3.3±2.9
Wrestling	5121±209	43.3±10.5	1.3±0.9	2.0±1.6	21.3±31.6	18.0±2.2	10.0±5.4	0.3±0.5	2.5±2.4	2.3±2.2
Cycling	22958±497	95.3±9.9	43.5±5.3	20.8±2.5	16.0±14.6	16.8±5.1	59.5±5.7	6.5±5.4	2.31±0.9	56.8±14.2
Taekwondo	1980±195	8.5±2.4	0.5±0.8	0.8±0.9	2.0±3.4	8.3±2.8	1.5±0.6	0.3±0.5	0.7±0.6	0.8±0.5
Judo	4449±480	17.5±7.8	0.3±0.5	1.8±1.5	6.3±6.7	13.0±3.6	8.5±3.9	0.3±0.5	1.5±1.7	2.0±2.2
Athletics	29764±2678	148.8±6.7	30.8±8.2	13.3±3.2	48.5±60.8	24.3±6.1	39.3±7.0	2.0±1.1	3.0±2.8	31.3±3.6
Canoe/kayaking	4293±278	17.8±2.5	1.3±0.9	1.0±0.0	14.8±22.9	1.2±0.5	3.8±2.2	0.5±0.6	1.5±0.7	1.5±1.2
Shooting	2204±627	2.3±2.1	0.0±0.0	0.8±0.9	1.0±0.8	5.0±2.6	2.8±1.5	0.3±0.5	0.5±0.6	0.0±0.0
Triathlon	3946±324	5.5±2.1	1.5±1.7	5.8±2.8	3.0±3.0	2.5±1.3	5.5±1.9	0.3±0.5	0.0±0.0	4.8±0.5
Rowing	4834±369	10.5±4.0	0.3±0.5	2.3±1.5	4.3±5.3	7.8±3.5	8.5±4.2	0.0±0.0	0.0±0.0	1.0±0.8
Aquatics	13851±1546	25.8±9.7	1.8±2.2	11±5.5	11.3±17.3	9.5±4.8	20.5±6	0.3±0.5	2.3±2.1	7.0±2.2
Tennis	4699±896	7.5±7.7	0.8±0.9	0.3±0.5	3.3±3.8	2.3±1.9	8.8±6.3	0.3±0.5	1.5±1.3	2.8±0.9
Gymnastics	2270±138	0.8±0.5	0.0±0.0	0.3±0.5	0.7±1.2	4.5±2.9	8.3±3.9	0.0±0.0	0.3±0.6	0.3±0.5
Biathlon	2062±313	1.5±1.9	0.5±1.0	0.0±0.0	5.6±7.4	0.8±0.9	0.3±0.6	0.0±0.0	0.0±0.0	1.0±1.4
Fencing	1644±123	1.8±1.5	0.0±0.0	0.8±0.9	0.0±0.0	1.3±0.9	0.8±0.9	0.0±0.0	0.8±0.5	1.3±0.9
Skating	4168±719	2.5±1.3	0.3±0.5	1.0±2.0	5.8±10.2	0.8±0.9	2.8±1.5	0.0±0.0	0.3±0.5	0.8±0.9
Skiing	5955±1283	0.8±0.5	1.3±1.9	1.8±0.9	3.3±2.1	2.0±1.8	2.8±0.5	0.0±0.0	0.5±1.0	7.8±11.1

Table 2. Number of samples and number of adverse analytical findings in team sports according to the categories of banned substances proposed by WADA

Team sports	Samples	Anabolic agents	Growth factors	β2-agonists	Hormones	Diuretics	Stimulants	Narcotics	Cannabinoids	Glucocorticoids
Rugby	7602±629	45.5±5.9	1.8±1.7	6.0±2.8	6.3±5.3	4.5±1.7	15.5±6.5	4.3±5.2	5.8±4.4	7.3±2.1
Ice hockey	3579±349	4.8±4.9	0.0±0.0	5.0±3.6	3.3±4.9	1.0±1.2	11.8±8.5	0.3±0.5	4.7±2.5	2.3±1.7
Basketball	5429±258	14.8±10.8	0.0±0.0	3.0±2.4	3.0±0.8	2.8±2.2	15.8±1.7	0.3±0.5	11.3±4.1	4.0±0.8
Handball	3790±223	8.0±4.9	0.0±0.0	4.3±3.2	1.3±1.5	1.3±0.5	6.5±3.4	1.5±1.7	2-0±0.8	0.8±1.5
Hockey	1550±112	5.0±3.2	0.0±0.0	0.3±0.5	0.8±0.5	0.5±0.6	1.5±1.3	0.0±0.0	1.3±0.6	0.8±0.5
Volleyball	4404±151	12.0±6.7	0.0±0.0	1.3±1.5	1.7±2.8	2.3±0.9	5.5±2.5	0.0±0.0	2.0±1.4	1.5±1.0
Football	33487±2553	61.8±12.6	1.8±1.7	9.0±2.7	6.8±3.3	12.0±7.2	42.5±1.7	2.3±3.3	10.5±5.8	28.0±7.4

Table 3. Between-sport comparison distribution of adverse analytical findings in individual sports according to the categories of banned substances proposed by WADA.

Individual sports	**Anabolic agents**	**Peptide hormones/ growth factors**	**β2-agonists**	**Hormone/ metabolic modulators**	**Diuretics/ masking agents**	**Stimulants**	**Narcotics**	**Cannabinoids**	**Glucocorticoids**	**β-blockers**
Weightlifting	+	-	-	-	-	-	-	-	-	-
Boxing	-	-	•	•	+	•	•	+	-	-
Wrestling	•	-	-	+	+	-	•	•	-	-
Cycling	-	+	+	-	-	+	+	-	+	-
Taekwondo	•	•	•	•	+	-	•	•	•	-
Judo	•	-	•	•	+	•	•	•	-	-
Athletics	+	+	-	+	-	-	•	-	•	-
Canoe/kayaking	+	•	•	+	-	-	•	•	-	-
Shooting	-	•	•	•	+	•	•	•	-	+
Triathlon	-	•	+	•	•	•	•	•	+	-
Rowing	-	-	•	•	•	+	•	•	-	-
Aquatics	-	-	+	•	•	+	•	•	•	-
Tennis	-	•	•	•	•	+	•	+	•	-
Gymnastics	-	•	•	-	+	+	•	•	•	-
Biathlon	-	•	•	+	•	•	•	•	•	-
Fencing	•	•	•	•	•	•	•	+	•	-
Skating	-	•	•	+	•	•	•	•	•	-
Skiing	-	•	•	•	•	•	•	•	+	-

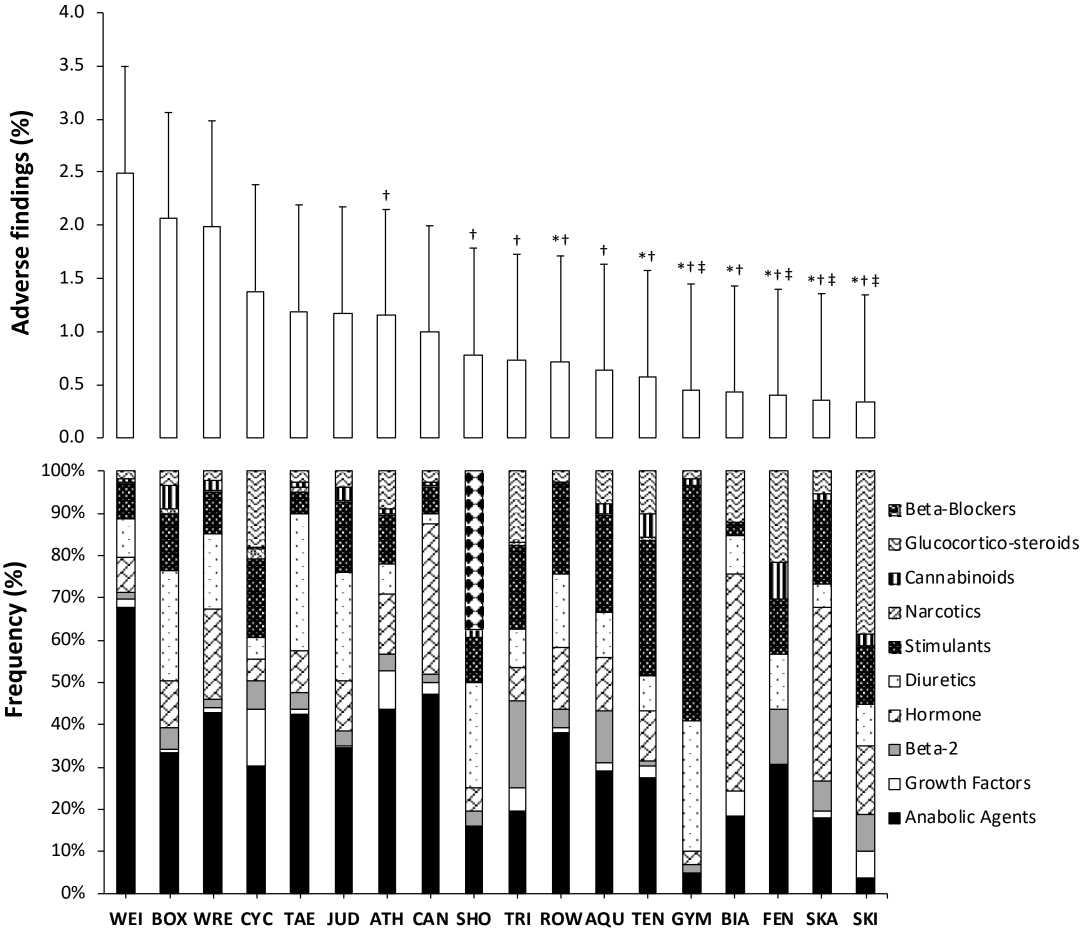
(+) Depicts that the proportion of adverse analytical findings for this category was higher than expected at ($p<5.0\times10^{-2}$).
(-) Depicts that the proportion of adverse analytical findings for this category was lower than expected at ($p<5.0\times10^{-2}$).
(•) Depicts that the proportion of adverse analytical findings for this category is similar to expected.

Table 4. Differences in distribution of adverse analytical findings in team sports according to the categories of banned substances proposed by WADA.

Team sports	Anabolic agents	Peptide hormones/ growth factors	β2-agonists	Hormone/ metabolic modulators	Diuretics/ masking agents	Stimulants	Narcotics	Cannabinoids	Glucocorticoids
Rugby	+	+	•	•	•	-	+	-	-
Ice hockey	-	•	+	•	•	+	•	•	•
Basketball	-	•	•	•	•	•	•	+	•
Handball	•	•	+	•	•	•	+	•	-
Hockey	+	•	•	•	•	•	•	•	•
Volleyball	+	•	•	•	•	•	•	•	•
Football	•	•	-	-	•	•	•	•	+

(+) Depicts that the proportion of adverse analytical findings for this category was higher than expected at ($p<5.0\times10^{-2}$).
(-) Depicts that the proportion of adverse analytical findings for this category was lower than expected at ($p<5.0\times10^{-2}$).
(•) Depicts that the proportion of adverse analytical findings for this category is similar to expected.

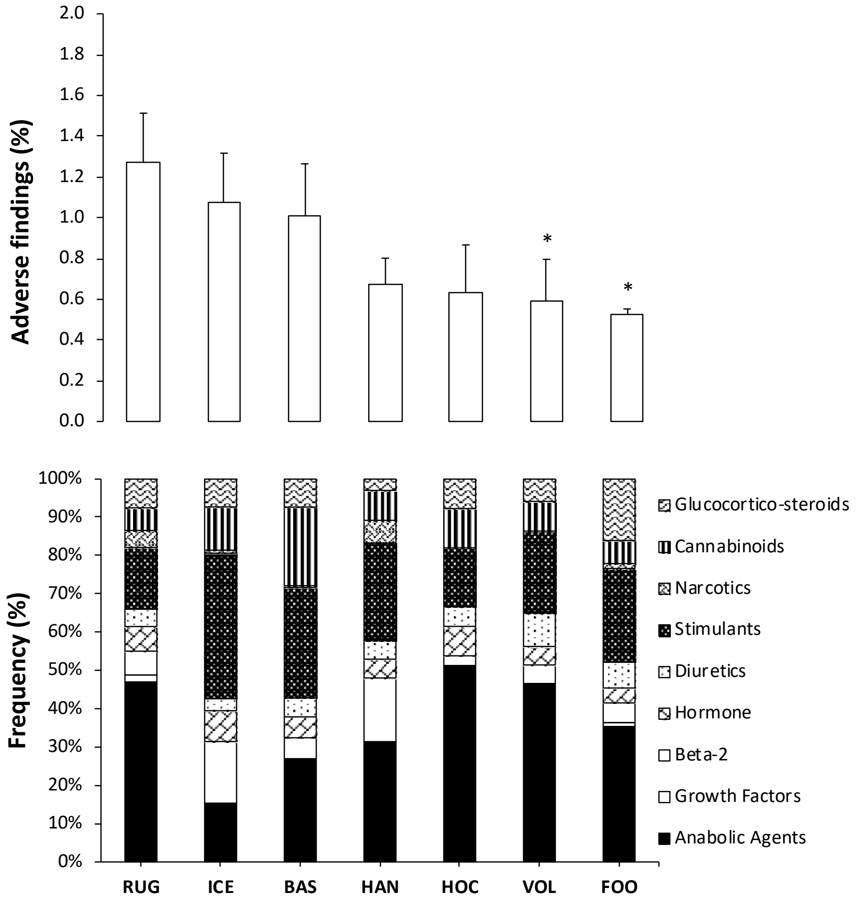
Figure 1. (A) Percentage of adverse analytical findings and (B) distribution of adverse analytical findings per category of banned substances in individual sports. The data are mean ± SD for each sport between 2014 to 2017.



WEI = Weightlifting; BOX = Boxing; WRE = Wrestling; CYC = Cycling; TAE = Taekwondo; JUD = Judo; ATH= Athletics; CAN = Canoe/Kayaking; SHO = Shooting; TRI = Triathlon; ROW = Rowing; AQU = Aquatics; TEN = Tennis; GYM = Gymnastics; BIA = Biathlon; FEN = Fencing; SKA = Skating; SKI = Skiing. The category of "beta-blockers" has been included in this graph although this group of substances is only banned in shooting and in some specialities of skiing.

(*) Different from WEI at (p<5.0×10^{-2}); (†) Different from BOX at (p<5.0×10^{-2}); (‡) Different from WRE at (p<5.0×10^{-2}).

Figure 2. (A) Percentage of adverse analytical findings and (B) distribution of adverse analytical findings per category of banned substances in team sports. The data are mean ± SD for each sport between 2014 to 2017.



RUG = Rugby; ICE = Ice Hockey; BAS = Basketball; HAN = Handball; HOC = Hockey; VOL = Volleyball; FOO = Football. The category of "beta-blockers" is not included in this graph because this group of substances is not banned in team sports.

(*) Different from RUG at (p<5.0×10^{-2}).