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Challenges of talent development in alpine ski racing: a narrative review

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ABSTRACT
Alpine ski racing is one of the most popular sports in many countries; nevertheless, selection disadvantages and severe injuries result in high dropout rates. In this review we summarize existing knowledge about the specific challenges associated with selection bias and injuries, and their effects on talent development in ski racing.

The relative age effect (RAE) appears in all age categories of national Austrian and international alpine ski racing. Relatively younger athletes seem to only have a chance for selection if they are early maturing. Talent selection processes should consider both the biological maturity status as well as the relative age; additionally, a competition system based on a rotating cut-off date might contribute to a reduction of RAE. Youth and adolescent ski racers report lower injury rates compared to World Cup athletes. The knee was the most affected body part in relation to traumatic injuries. The most frequently reported overuse injuries were knee pain (youth) and low back pain (adolescent level). Athlete-related modifiable risk factors were core strength, neuromuscular control, leg extension strength and limb asymmetries. Based on these findings, prevention measures should be expanded to contribute to long-term injury prevention. In future research more multi-disciplinary, longitudinal studies should be performed.

Introduction
Alpine ski racing is one of the most popular winter sports in many countries all over the world. Thousands of children specialize at an early age with hopes of becoming professional and successful athletes. The peak performance in alpine ski racing, which is considered as a complex sport and characterized by high physical and tactical capacities, is mostly achieved between the age of 26–28 years (Raschner, Müller, & Hildebrandt, 2015). The specialization at an early age combined with a relatively long competitive life needs to be considered when implementing strategies to develop talent due to the fact that alpine ski racing is a uniquely early specialization sport. However, the number of those children has decreased in the last years, at least in Austria (Raschner et al., 2015). Simultaneously, the number of Austrian alpine ski racers who have dropped out of the sport as a result of their lack of success or due to selection disadvantages, respectively, has increased (Raschner et al., 2015). Additionally, many young athletes are disadvantaged in their career development because of the loss of training time due to severe injuries. These recent trends indicate the loss of a large number of talented youth alpine ski racers during the development process, at least in Austria, which might be true also for other countries. The mechanisms behind this loss of talent are still not clear. It might be assumed that talent development systems do not consider important aspects such as selection disadvantages, injuries, biological maturation and psychological factors, among others. In this context, it seems especially important to bring together all proven findings in the context of talent development in alpine ski racing with respect to the challenges athletes have to deal with during their careers, two of which are the relative age effect and injuries.

Therefore, the main goal of this narrative review was to summarize existing knowledge with respect to the above mentioned challenges, in order to suggest preventive measures that help optimise the development of talent in alpine ski racing.

Methodology
The present article is a comprehensive review of the existing knowledge regarding the two main challenges in talent development in youth alpine ski racing, the relative age effect and injuries, including injury risk factors. Given the small number of studies in this area, and based on the review by Spörrl, Kröll, Gilgien, and Müller (2017), a narrative review was considered to be methodologically more appropriate than a systematic review. It provides an overview of exploratory research.

Three databases (PubMed, MEDLINE, and Web of Science) were searched to identify the relevant studies. In addition, articles were selected by hand search. The key search terms used were “(youth) alpine ski racing”, “relative age effect”, “maturity”, “injury and injury risk factors” and combinations thereof.

The relative age effect in alpine ski racing
The phenomenon of the relative age effect (RAE) is well investigated and represents a “selection error” in various types of sports. Despite the intention of grouping children and youth athletes into competition categories based on their chronological age with the aim of guaranteeing fair competition and reflecting age-related
development, an age difference of up to twelve months between individuals is possible. In this context, the RAE is defined as the over-representation of relatively older athletes within one selection year compared to relatively younger athletes (Cobley, Baker, Wattie, & McKenna, 2009; Helsen, Van Winckel, & Williams, 2005; Musch & Grondin, 2001).

Talent identification systems are based on selection biases that confuse maturation for talent. The so-called maturation-hypothesis explaining the RAE in sports is based on the assumption that the relative age of an athlete is related to his/her cognitive and physical maturation; thus, maturational differences between relatively younger and relatively older athletes seem to influence the favorable selection of the older athletes (Baker, Janning, Wong, Cobley, & Schorer, 2014). The short-term consequences are that relatively older and earlier maturing athletes seem to be potentially more “talented” and are favourably selected, whereas relatively younger and less mature athletes often do not get the chance to reach the elite level, despite their talents and efforts, and they often drop out of sport early (Malina, Eisenmann, Cumming, Ribeiro, & Aros, 2004; Romann & Cobley, 2015). Talent in a sport does not depend on the birth month; as a consequence, the existence of a RAE indicates that the talent development systems in these sports are biased and that many talented young athletes are overlooked (Cobley et al., 2009; Lames, August, Dreckmann, Görsdorf, & Schimanski, 2008).

The existence of the relative age effect in alpine ski racing

The RAE exists particularly in culturally popular and important sports, and in sports with high demands on strength and power (Cobley et al., 2009; Helsen et al., 2005; Musch & Grondin, 2001). Not surprisingly, a RAE was proven to exist in alpine ski racing as well. As shown in Table 1 and Figures 1a–c and 2, the RAE is present in all age categories and at both national and international levels. It starts to exist at the youngest levels of national youth ski racing (>7 years) in Austria and continues all the way up to the elite level, the FIS World Cup. The effect is more pronounced at the youth/adult level compared with the elite level; the greatest effect sizes (medium: \( \omega = 0.5–0.74 \)) were found at the international youth level among participants of the alpine ski races at the Youth Olympic Games (YOG) 2012 in Innsbruck (Raschner, Müller, & Hildebrandt, 2012) and the International Children’s Games (ICG) 2016 in Innsbruck (Müller, Hildebrandt, & Raschner, 2017). It might be hypothesized that the selection pressure prior to international youth events such as the YOG and the ICG might be very high because per country only one to two athletes per gender are allowed to participate in each discipline (Raschner, Müller, & Hildebrandt, 2012; Müller, Hildebrandt, & Raschner, 2017a). As a result, it might be assumed that the high selection pressure leads to stronger RAE compared to events in which more athletes are allowed to participate. However, medium effects were also present at the national youth level in Austria. The extent of the RAE seems to diminish at the World Cup level (Baker et al., 2014; Bjerke, Pedersen, Aune, & Lorås, 2016; Müller et al., 2012). This trend is in line with studies in other types of sport which report a less severe RAE in older participants, implying that early development processes are more germane in the creation of a RAE (Schror, Cobley, Büsch, Bräutigam, & Baker, 2009). It might be hypothesized that in some specific stage of the career, the supposedly more talented, relatively older athletes no longer have the advantages due to their relatively older ages; therefore, they no longer have performance advantages and as a result drop out of sport at an advanced stage of their careers. In this context, Bjerke et al. (2016), found relatively younger athletes to be more successful at the World Cup level compared to relatively older ones. Nevertheless, there is, however, the possibility that more talented young athletes who were relatively younger, had already dropped out of sport much earlier due to their chronological age disadvantage. Based on this notion and the fact that all age categories of national and international levels of alpine ski racing are affected by the RAE, strategies in the talent development systems have to be changed to ensure greater fairness and to avoid losing so many talented youth ski racers.

Published reports suggest that the occurrence of the RAE in female athletes is less consistent (Cobley et al., 2009). Some researchers did not report the existence of a RAE in female populations; if a RAE was present, often a weaker RAE was found among the females compared with their male counterparts. The reasons were seen in the lower popularity of female sports and fewer and less impactful maturational differences (Cobley et al., 2009). Inconsistent results also were found in alpine ski racing; however, in the majority of categories a RAE was present among female athletes. As shown in Table 1, the RAE is present among female ski racers at the national youth level in Austria, with the exception of the National teenager cup races with athletes aged 12–15 years (Müller, Hildebrandt, & Raschner, 2015). At the Austrian national youth final races, even larger effect sizes were observed among the females (Müller, Müller, Hildebrandt, & Raschner, 2016). At the international youth level, a RAE was found in all female participants of ski races at the international championships (Müller et al., 2012; Raschner, Müller, & Hildebrandt, 2012; Müller, Hildebrandt, & Raschner, 2017), except for the EYOF, where a RAE was present only for the total group (Müller, Hildebrandt, Schnitzer, & Raschner, 2016). The earlier onset of puberty might explain the larger RAE found among female athletes at the youth level (until the ages of approximately 12 years) because in this period maturational differences might be higher between female athletes than between male athletes and therefore, a greater influence of maturity on the selection might be present among the female athletes. A larger effect was found for females at the FIS Junior World Ski Championships (Müller et al., 2012) and the ICG (Müller, Hildebrandt, & Raschner, 2017). At the elite level, the FIS World Cup, inconsistent results were found. Müller et al. (2012), who investigated those World Cup athletes who won at least one World Cup point in one discipline in the seasons 2006/07–2010/11, and Bjerke et al. (2016), who investigated the Top-50 athletes of 20 years, could not find a significant RAE among female ski racers. Yet, Baker et al. (2014), who investigated participating athletes in the FIS World Cup that were born 1970 or later, did find a RAE among the females. All in all, it can be concluded that the female variant of alpine ski
racing is strength and power related, as well, and in several countries, especially in Austria, the selection pressure is also high in the female context. Therefore, the RAE also represents a problem among female ski racers.

### The influence of relative age on performance in alpine ski racing

The relative age not only influences the participation rate in alpine ski racing, but also performance in general. Relatively older athletes were more successful at the national youth level in Austria (Kids Cup and Teenager Cup; Müller, Hildebrandt, & Raschner, 2015) and the international youth level (YOG; Raschner, Müller, & Hildebrandt, 2012). In Austria, a highly significant influence of the relative age on performance was assessed among Kids Cup and Teenager Cup athletes with more relatively older athletes placed in the top-3 (Müller, Hildebrandt, & Raschner, 2015). In addition, most medals (15 out of 19) at the YOG in 2012 were won from athletes of the first and second relative age quarters (Raschner, Müller, & Hildebrandt, 2012). These results indicate that relatively younger athletes have less chance of being successful in alpine ski racing, which might contribute to lower motivation for continuing in this sport, and as such might increase the drop-out rate among relatively younger athletes compared to relatively older ones (Müller, Hildebrandt, & Raschner, 2015). However, at the national youth level, the results of only one season and only from
Figure 2. Schematic representation of the existence of the relative age effect in all categories of national and international levels of alpine ski racing.

Figure 1a–c The relative age quarter distributions of a) international elite, b) international youth/adolescent, and c) national youth ski racers (summary of existing studies).
one country, and at the YOG, the results of only one event with diverse disciplines, were considered in the analyses. Longitudinal data that examine whether the relative age has an influence on the long-term performance of athletes as well as data from different countries are needed.

At the World Cup level, Bjerke et al. (2016) reported that relatively younger male athletes might be more successful because they seem to have accumulated on average more World Cup points compared to relatively older ones. However, the authors did not consider several factors (such as the number of seasons per athlete, injuries, the number of disciplines per athlete), thus, the results have to be interpreted with caution.

**Factors that influence the relative age effect in youth alpine ski racing**

Before strategies in the talent development systems can be changed in order to minimize the RAE, the influential mechanisms have to be assessed in each specific sport (Wattie, Schorer, & Baker, 2015). With respect to influential factors on the RAE in youth alpine ski racing in Austria, three aspects were considered: level of physical performance (Müller, Müller, Kornexl, & Raschner, 2015); anthropometric characteristics (Müller, Müller, Hildebrandt, Kornexl, & Raschner, 2015); and biological maturity status (Müller, Müller, Hildebrandt, Kapelari, & Raschner, 2015; Müller, Müller, Hildebrandt, & Raschner, 2016); Müller, Gonaus, Perner, Müller, & Raschner, 2017). Austrian youth ski racers across the four relative age quarters did not differ significantly in their level of physical performance (Müller, Müller, Kornexl, Hildebrandt, & Raschner, 2015c), which is in line with studies in other types of sport such as soccer (Carling, Le Gall, Reilly, & Williams, 2009) or rugby (Till, Cobley, O’Hara, Cooke, & Chapman, 2014). Thus, the authors concluded that coaches select similar archetypal athletes: relatively younger athletes have to have an elevated level of physical fitness (relative to their age) in order to be selected in the talent development process in alpine ski racing in Austria (Müller, Müller, Kornexl et al., 2015). A sport in which a high level of physical fitness is required (Raschner et al., 2005; Raschner, Patterson, Platzer, & Lembert, 2008; Turnbull, Kilding, & Keogh, 2009). In this context, the important role of coaches in the talent selection in youth ski racing is obvious, whose decisions are often based on race results and sometimes on the level of physical performance, as for example at entrance exams for ski boarding schools (Müller, Müller, Kornexl, & Raschner, 2015a). However, coaches must be aware that during puberty muscle growth can be slower than skeletal growth leading to uncoordinated movements and therefore, reductions in physical fitness performances are possible (Specker, Thiex, & Sudhagoni, 2015). A comparison group of non-athletes of the same age and from the same region as the youth ski racers performed significantly worse compared to the ski racers; a fact that underlines the importance of well-developed physical fitness in alpine ski racing (Müller, Müller, Kornexl et al., 2015). Additionally, in a study investigating injuries in youth ski racers, relatively younger athletes had lower percentages of traumatic injuries compared to relatively older athletes; as a consequence, the authors hypothesized that relatively younger athletes were physically more prepared and, therefore, less susceptible to injury (Müller, Hildebrandt, Müller, Oberhoffer, & Raschner, 2017).

Anthropometric characteristics were shown to have an influence on performance because athletes with higher body height and body mass had advantages (Raschner, Müller, Schwameder, Haid, & Männel, 1995). As a consequence, not surprisingly, a significant influence of body height and body mass on the RAE was assessed in Austrian youth ski racers (Müller, Müller et al., 2016). Relatively older athletes were significantly taller and heavier compared to their relatively younger counterparts, whereas the comparison group of non-athletes did not significantly differ from each other considering their relative age quartile (Müller, Müller et al., 2016). As a consequence, it might be assumed that anthropometric characteristics seem to further influence the RAE in alpine ski racing and that athletes born in the first relative age quarter might be favorably selected initially because of their advanced anthropometric characteristics and not because of their talent. However, data from different countries are needed in this context.

Biological maturity status was shown to have the greatest influence on the RAE. Athletes selected for national youth final races in Austria were significantly more mature compared to athletes participating only at the regional level (Müller, Müller et al., 2016). A significant difference (\(\mu = 0.42\)) from the expected normal distribution of early, normal and late maturing athletes was assessed among the athletes selected for national youth final races; 78.1% were normal maturing and 21.4% were early maturing with only 0.5% were late maturing. In addition, athletes of the first relative age quarter seemed to have an increased likelihood of selection for national final races independent of their biological maturity status. In contrast, relatively younger athletes might “only” have had a chance for selection if they were early maturing: nearly half of them (43.3%) were early maturing, whereas among relatively older athletes only 13.2% were early maturing (Müller, Gonaus, et al., 2017b). However, the biological maturity status was assessed using the non-invasive method of calculating the age at peak height velocity according to Mirwald, Baxter-Jones, Bailey, and Beunen (2002), which might not be the most accurate method. Nevertheless, the method was often used in studies among youth athletes and a good validity of the method was proven among youth ski racers (Müller et al., 2015). However, also with respect to the influence of biological maturity on talent selection data are available only from one country; therefore, studies investigating this aspect in different countries are needed.

**Possible solutions for reducing the relative age effect**

In various types of sport, several possible solutions for reducing the RAE have been mentioned, such as changing the age-group cut-off date, delaying the process of talent identification beyond stages of puberty and maturation, rotating the cut-off date, using competition groups based on height and weight, among others (Cobley et al., 2009). However, changing the cut-off date would only lead to a transfer of RAE (Cobley et al., 2009) and delaying the process of talent identification might help reducing the RAE also in alpine ski racing; nevertheless, it does not seem applicable in this sport. For reducing the RAE in alpine ski racing, Romann and Fuchslocher (2014) underlined that in individual sports, such as
in alpine ski racing, selections are often based on competition results and, as a result, competition systems and rules should be changed in order to possibly reduce the RAE. In addition, the fact that the RAE did not increase from the first level of national youth ski racing in Austria (Kids Cup) to the second level (Teenager Cup), indicates that the selection error has already taken place at or before the youngest level. These findings support the premise that strategies in the competition system have to be changed (Müller, Hildebrandt, & Raschner, 2015). In this context, Romann and Fuchslocher (2014) proposed implementing categories based on height and weight, or adapting the starting order in qualification races (relatively younger athletes should start first for the benefit of better races conditions), or implementing competitions that include more technical skills as criteria of performance and/or a correction factor (calculated by correlating race time with relative age). However, thus far the effectiveness of these suggestions has not been proven (Romann & Fuchslocher, 2014) and grouping athletes based on weight and height does not seem to be applicable in youth ski racing due to the organization of the competitions and it might lead to an ethical conflict when stressing youth athletes to eat less prior to competitions in order to be allowed to participate in another weight category etc.

Müller et al. (2012) suggested changing the classification of the competition categories based on a rotating cut-off date, as was recommended by Hurley, Lior, and Tracze (2001) in Canadian ice hockey. As illustrated in Figure 3 (modified according to Hurley et al., 2001), the cut-off date would change nearly every year for three months. During the development system in youth ski racing in Austria, which lasts for eight years, every athlete would run through every relative age quarter twice, and as a consequence, every athlete should gain nearly the same relative age advantages. Stakeholders positively evaluated the effectiveness of this system and its possible contribution to more fairness in talent development in alpine ski racing (Müller et al., 2012). In addition, it seems absolutely necessary that coaches and sporting federations generate their approaches to improve the fairness in age category competitions (Romann & Fuchslocher, 2014). The challenge in youth ski racing is to keep those athletes who are physically and psychologically disadvantaged (Romann & Fuchslocher, 2014) and delayed in their maturation (Müller, Müller et al., 2016) involved in the sport until they have fully matured. In this context, the rotating cut-off date system seems appropriate, even though the RAE might not disappear; however, it might contribute to keeping relatively and less mature athletes involved in the system until end of puberty. Additionally, the awareness of the coaches should be trained to consider diverse aspects in selection processes and to not be deceived by maturational advantages and early success. Selection processes have to consider the relative age and the maturation of an athlete.

Injuries and injury risk factors in youth and adolescent ski racing

The long-term process in injury prevention is suggested as a multi-stage sequence introduced by Van Mechelen, Hlobil, and Kemper (1992), which is presented by four steps. In a first step, it is necessary to epidemiologically assess the extent of the injury problem (injury incidence and severity). Second, the injury causes and mechanisms (risk factors) have to be assessed to be able to establish prevention measures in step 3. Finally, in the fourth step of the sequence, the effectiveness of these measures has to be proven. After this, the sequence has to be run through again in order to re-evaluate the process (Van Mechelen et al., 1992).

With respect to this sequence, many papers have already been published, the findings of which were summarized in a recent review article on injury prevention in alpine ski racing (Spörr et al., 2017). The authors demonstrated that alpine ski racing is a sport with a high risk of injury. In elite alpine ski racing (World Cup level), injury rates of more than 36 injuries/100 athletes have been reported, 36% of them being severe (time loss of more than 28 days) and partly career ending (Bere, Florenes, Nordsletten, & Bahr, 2013; Spörr et al., 2017). However, the main emphasis in studies with respect to injuries in alpine ski racing was placed on top-level athletes (World Cup), whereas studies among youth and adolescent athletes are rare (Spörr et al., 2017). In adolescent ski racing, with Austrian and Swedish athletes aged between 15 and 19 years, three studies have been published to date (Hildebrandt & Raschner, 2013; Raschner, Platterz, Patterson, Werner, Huber, & Hildebrandt, 2012; Westin, Alricsson, & Werner, 2012) and among Austrian athletes younger than

![Figure 3. The rotating cut-off date system modified for alpine ski racing (adapted from Hurley et al., 2001; modified according to Müller et al., 2012).](image-url)
15 years, three studies have been published or submitted (Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017c; Müller, Hildebrandt, Müller, Fink, & Raschner, 2017; Müller, Hildebrandt, Müller, Fink, & Raschner, accepted). Considering the previously described four-step-sequence (Van Mechelen et al., 1992), three studies (Hildebrandt & Raschner, 2013; Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017; Westin et al., 2012) were performed with respect to the first step (injury epidemiology) and three studies (Müller, Hildebrandt, Müller, Fink, et al., 2017d; Müller et al., accepted; Raschner, Platzer, et al., 2012b) followed the second step (injury etiology).

**Traumatic and overuse injuries (first step – injury epidemiology)**

Table 2 represents the details of the three studies performed with adolescent (Hildebrandt & Raschner, 2013; Westin et al., 2012) and youth ski racers (Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017). With respect to traumatic injuries, relatively low incidences (0.86–1.7/1000 hours of (ski)training) and rates (0.63–0.67/athlete) were reported, which were slightly higher than at the elite level (36.7 injuries/100 athletes) (Spörri et al., 2017). A relatively low prevalence (0.28/1000 hours of training) of overuse injuries was assessed at the youth level (Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017), whereas at the adolescent level, more than 50% of the athletes had at least one overuse injury (Hildebrandt & Raschner, 2013). However, due to the differences in the reporting methods (prospective self-reporting; retrospective questionnaires; prospective data base), direct comparisons are difficult to carry out. In contrast to the elite level (Bere et al., 2013), none of the three studies found any gender-specific differences in the occurrence of injuries. The authors hypothesized that the reason might be the similar training-load exposures of boys and girls (Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017). Hildebrandt and Raschner (2013) found a higher risk for traumatic injuries during the winter season and a higher risk for overuse injuries during the summer season.

With respect to traumatic injuries, the most affected body part was the knee (36.5–41%) or the lower extremities in general, which is in line with findings at the elite level (Spörri et al., 2017). Of the adolescent Austrian youth ski racers, 13.5% sustained a rupture of the anterior cruciate ligament (ACL) (Hildebrandt & Raschner, 2013), which is the most frequently reported traumatic injury at the elite level, as well (13.6%; Spörri et al., 2017). At the youth level, only one male athlete suffered an ACL rupture; with this finding, the authors hypothesized based on Kubo, Kanehisa, Kawakami, and Fukanaga (2001), that the elastic properties of tendon structures in the growing athlete are higher and more compliant compared to the full-grown athlete (Müller, Hildebrandt, Müller, Oberhoffer et al., 2017). Nearly half of the traumatic injuries at the youth level affected the bones (46.1%), including physeal fractures (Müller, Hildebrandt, Müller, Oberhoffer et al., 2017), which might be explained by the fact that in youth athletes the physis is weaker than the ligaments and, therefore, fractures are more likely to occur (Kubo et al., 2001).

At the adolescent level, low back pain was the most reported overuse injury and problems with the trunk/back were more than half of the overuse injuries, followed by injuries of the lower extremities (Hildebrandt & Raschner, 2013). At the youth level (Müller, Hildebrandt, Müller, Oberhoffer, et al., 2017), however, the knee was again the most affected body part (> 90%); several athletes suffered from unspecified, but self-limiting knee problems, as was also the case in other types of youth sports (Leppänen, Pasanen, Kujala, & Parkkari, 2015). It might be hypothesized that the older the ski racers are, or the higher the level of ski racing is, the more low back pain plays a role, whereas at a younger age, athletes have to deal with knee pain more than with back problems. Individual biological capacities and

| reference | Westin et al. (2012) | Hildebrandt and Raschner (2013) | Müller, Hildebrandt, Müller, Oberhoffer, and Raschner (2017c) |
|-----------|----------------------|-------------------------------|---------------------------------------------------------------|
| group of ski racers | adolescent | adolescent | youth |
| nation | Sweden | Austria | Austria |
| age group | 16–19 | 15–18 | 9–14 |
| sample size | total | 431 | 104 | 82 |
| | males | 215 | 61 | 51 |
| | females | 216 | 43 | 31 |
| study design | prospective | retrospective self-reporting | retrospective questionnaires |
| study period | 5 years | 2 years | 2 years |
| traumatic injuries | incidence rate/athlete | 1.7/1000 ski hours | not reported | 0.86/1000 training hours |
| | severity | 0.67 | 46% moderate | 44% moderate |
| | most affected body parts | 49% severe | 41% knee | 29% lower extremities |
| overuse injuries | prevalence rate/athlete | not investigated | not reported | 0.28/1000 training hours |
| | severity | not investigated | not investigated | 0.21 |
| | most affected body parts | not investigated | not investigated | 55% trunk/back |
| | | | | 12% hip/thigh |
changes of passive and active structures during growth need to be considered to minimize overuse injuries (Magnusson, Hansen, & Kjaer, 2003).

Most of the traumatic injuries were classified as moderate (44%–48%) or severe (12%–49%); and most of the overuse injuries were categorized as moderate (34%–47%), severe (17.6%) or as injuries that did not cause an absence from training (37%). In this context, the diverse reporting methods have to be considered because the self-reporting (Westin et al., 2012) or the retrospective (Hildebrandt & Raschner, 2013) designs might have led to a recall bias. In addition, Müller, Hildebrandt, Müller, Oberhoffer et al. (2017) considered only those injuries that have led to a time loss of at least one day. However, it has to be considered that data were available only from Austria (youth and adolescent level) and Sweden (adolescent level); studies involving athletes from diverse countries are needed.

**Injury risk factors (second step – injury etiology)**

In order to be able to derive effective preventive measures that reduce the injury risk, injury causes/risk factors have to be recognized (Van Mechelen et al., 1992; Spörrl et al., 2017). Spörrl et al. (2017) divided the risk factors in elite alpine ski racing into four categories: 1) athlete-related; 2) equipment-related; 3) course-related; and 4) snow-related injury risk factors. In addition, Raschner, Platzer et al. (2012) differentiated modifiable and non-modifiable athlete-related risk factors based on the model of Meeuwisse (1994). Modifiable risk factors would be skill level (skiing technique, falling technique), psychological factors and physical fitness. Non-modifiable risk factors are anatomical, hormonal and demographic factors. At the youth and adolescent levels, only modifiable and non-modifiable athlete-related risk factors have been investigated.

Raschner, Platzer, et al. (2012b) retrospectively investigated 15- to 18-year old Austrian youth ski racers over a period of 10 years and detailed the modifiable risk factors for sustaining an ACL-rupture. Irrespective of gender, core strength was shown to be a critical factor for preventing ACL ruptures in young skiers. Core strength imbalances with too strong trunk flexor muscles, or too weak trunk extensor muscles, characterized injured male athletes and represented a critical risk factor. Furthermore, among male athletes, the reactive strength index (RSI; drop jump jumping height [mm]/ground contact time [ms]), as well as the relative maximal isometric unilateral leg extension strength, were significant injury risk factors (athletes with higher values were at a lower injury risk); however, no differences were found between injured and non-injured athletes.

Müller, Hildebrandt, Müller, Fink, and Raschner (2017d) evaluated possible modifiable (skill level – skiing technique; physical fitness) and non-modifiable (anthropometric characteristics; biological maturity status) risk factors in Austrian youth ski racing. With respect to the importance of physical fitness at the youth level, similar results were found to those of Raschner, Platzer et al. (2012) at the adolescent level. Athletes with better core flexion strength, a shorter drop jump contact time and a higher RSI were at a lower injury risk, in general. With respect to injury severity, the following modifiable risk factors were found to be significant: athletes with a smaller core flexion to extension strength ratio, a shorter drop jump contact time, and a higher RSI were more likely to experience less severe injuries. However, in both analyses, significant differences between injured and non-injured athletes, or between athletes with mild, moderate or severe injuries were only found in the RSI. Concerning the non-modifiable risk factors, the following parameters were found to be significant. First, athletes with higher body height or higher body weight and higher sitting height were at a lower injury risk. Second, more mature athletes were likely to have less severe injuries compared to less mature athletes. Another study concentrated on the role of limb asymmetry as a possible modifiable risk factor in youth ski racing (Müller et al., accepted). The findings showed that the limb symmetry index (dominant leg/non-dominant leg * 100) of the unilateral maximal isometric leg extension strength represents a significant injury risk factor in youth ski racers. The higher the difference between dominant and non-dominant leg was, the higher the injury risk of an athlete.

Summarizing these findings, core strength, neuromuscular control (drop jump), limb asymmetries, anthropometric characteristics and the biological maturity status all represent significant injury risk factors in youth ski racing. (Müller, Hildebrandt, Müller, Fink et al., 2017; Müller et al., accepted) However, all these studies were conducted in Austria and the results might only represent Austrian athletes, whereas the reproducibility of the findings as well as the variance that may exist across countries have to be examined in future studies.

**Possible preventive measures (third & fourth step – injury prevention measure and evaluation)**

At the youth and adolescent levels of ski racing, no study has been performed so far that has elaborated on possible preventive measures to reduce risk of injury. Prevention measures should concentrate on core strength, neuromuscular control and limb (a)symmetry, as well as other risk factors. Intervention studies focusing on these aspects should be performed in order to better understand the role of these factors in the long term injury prevention of (youth) ski racers. (Müller, Hildebrandt, Müller, Fink et al., 2017; Müller et al., accepted) Raschner, Platzer et al., (2012).

**More multi-disciplinary, longitudinal research is needed in (youth) alpine ski racing**

In Austria, children start skiing at an early age (3–4 years) and join ski clubs by the age of five to six years. The first selection (for skiing specific secondary modern schools) takes place at the age of 9 to 10 years and the second selection (for skiing specific grammar schools and junior provincial ski teams) is at the age of 15 to 16 years. The international female peak performance age in alpine ski racing is slightly higher than 26 years, whereas the male peak performance age is approximately 28 years (Raschner et al., 2015). As a consequence, talent development in alpine ski racing lasts for
approximately 15 years. However, multi-disciplinary and longitudinal studies focusing on the diverse influential factors (e.g., physical performance, psychological factors, technical and tactical skills) on the talent development in alpine ski racing are lacking.

Research in (youth) alpine ski racing has focused on selection biases and injuries. However, important aspects such as psychological factors (e.g., grit, resilience, anxiety control, mental toughness) and possible issues leading to burnout have not been investigated, so far. The importance of psychological training in alpine ski racing as well as the acceptance of it by athletes was underlined more than 20 years ago (Amesberger, 1997). Among other federations, the German Skiing Federation focuses on several aspects of psychological training in the talent development of youth ski racers, in which, apart from the sport psychological basic skills, the optimization of personality variables is of great significance. Processes such as performance motivation and stamina represent important talent development criteria in order to be able to maintain performance-orientated training over a longer period of time. In this context, a close cooperation of coaches and sport psychologists is needed (Engbert & Beckmann, 2009). Nevertheless, longitudinal studies focusing on the effectiveness of psychological training techniques on ski racing performance, as well as on performance relevant psychological variables are missing. However, in general, only a limited number of isolated studies have longitudinally examined psychological variables associated with athlete development (Morris, 2000). According to Cobley and Till (2017), the reasons for this paucity of research are that there are multiple psychological constructs, many of which are latent, such as self-regulation and motivation, theoretically driven and multi-faceted. As a consequence, these facts make them challenging to validly and reliably quantify (Cobley & Till, 2017). Nevertheless, in general in youth sports, athletes that are naturally in possession of abundant motivation and self-regulation skills are the athletes that continue to stay in sport and that become elite athletes; these skills can be developed (Elbe & Wikman, 2017). In this context, a more multi-disciplinary approach seems necessary to better understand the multi-faceted talent development process in ski racing. In other types of sport, for example in soccer, associations of psychological variables (perceived psycho-social stress: e.g., well-being, sleep quality; sport-stress: e.g., emotional exhaustion, feeling less fit and in shape) and injury and illness rates were found (Brink et al., 2010; Cobley & Till, 2017). Additionally, studies focusing on issues related to burnout among youth ski racers have to be assessed (Larsen & Alfermann, 2017). High dropout rates were reported (Raschner et al., 2015), of which only some might be attributed to selection disadvantages and injuries. It can by hypothesized that high percentages of burn-outs during the talent development in ski racing might be due to psychological factors such as failure, anxiety control, twofold pressure of school and sport, reduced leisure time, motivation problems and social conflicts, among others (Raschner et al., 2005). However, measuring burnout is very difficult as it is more of a continuum rather than a state. In addition, the role of parents, financial aspects and reasons attributed to the sporting system (Larsen & Alfermann, 2017) as well as (under)recovery and overtraining (Pelka & Kellmann, 2017) should be considered. These issues have to be assessed in the context of alpine ski racing in the future.

The importance of a high level of physical fitness in alpine ski racing was reported in several studies (Raschner et al., 2005; Raschner, Patterson, Platzner, & Lembert, 2008; Turnbull et al., 2009; among others). Nevertheless, longitudinal studies focusing on the development of physical fitness of youth ski racers are missing, even though physical development is the most widely investigated area in talent identification and development (Cobley & Till, 2017). Apart from that, the role of technical skills in the talent development in ski racing was only investigated with respect to injury risk factors, even though technical skills are one selection criterion at entrance exams for ski boarding schools in Austria (Müller, Hildebrandt, Müller, Fink et al., 2017). Next to technical skills, tactical skills seem to be important aspects in the talent development, such as anticipation, visual search and decision-making. However, both aspects are not easy to assess due to methodological external and criterion validity related difficulties (Cobley & Till, 2017). Nevertheless, future longitudinal studies should focus on these aspects in order to get a multi-faceted picture of talent development in alpine ski racing.

With respect to all previously mentioned aspects (psychological variable, physical fitness, technical and tactical skills) multi-disciplinary and longitudinal studies in alpine ski racing are missing in order to outline possible differences in developmental profiles of successful and less successful athletes. Additionally, studies showing promising developmental profiles of athletes of different countries and skill levels seem to be of great importance in order to elaborate the generality and specificity of expertise in this sport.

Conclusions

Selection criteria in alpine ski racing are effectively based on early biological development and a relatively older age, at least in a country like Austria. It can be hypothesized that relatively younger and late maturing athletes seem to be marginalized or totally excluded; they seem to be suppressed by the relative age disadvantage associated with inexperience (Torres-Unda et al., 2013; Müller, Gonaus, et al., 2017b). A system based on a rotating cut-off date in combination with considering the biological maturity status and the relative age in selection processes might be useful (Müller et al., 2012; Müller, Gonaus, et al., 2017b). Additionally, the existence of the RAE and the consequences for talent selection and development should be pointed out to youth coaches. Educational programmes should present research results for practical applications.

The epidemiological data of reported traumatic and overuse injuries in youth and adolescent ski racing are summarized in Figure 4. A regular monitoring of training load and occurring injuries is essential to quantify risk factors. With
respect to risk factors (second step in injury prevention sequence), published studies in youth ski racing concentrated on athlete-related injury risk factors (see Figure 4). Physical fitness parameters seem to play a central role in injury prevention in youth ski racers. A regular screening program to identify pathophysiological conditions, asymmetries and strength weaknesses, as well as regular physiotherapy examinations were proposed (Müller, Hildebrandt, Müller, Oberhoffer et al., 2017). In addition, Raschner et al. (2015) underlined the importance of regular physical fitness testing to compare the results with age- and gender-specific norm data to identify weaknesses as early as possible, and to control the individual development of the athletes in the diverse performance relevant parameters. In this context, further longitudinal studies are required to explore the appropriate and individual pace of development. The non-modifiable risk factors also have to be considered in the talent development of young ski racers. Coaches have to consider the diverse maturity statuses and growth rates of the athletes and training processes should be maturity adequate to prevent especially late maturing athletes from sustaining injuries (Müller, Hildebrandt, Müller, Fink et al., 2017). However, the effectiveness of these possible preventive measures has to be evaluated.

Alpine ski racing is a sport in a changing outdoor environment that represents a multifactorial nature of injury causes (Spörri et al., 2017). Therefore, further studies are necessary that concentrate on other types of possible injury risk factors in youth and adolescent ski racing (equipment-, course-, and snow-related factors). In addition, studies with respect to the third and fourth steps in the Van Mechelen et al. (1992) sequence are necessary at the youth and adolescent levels (see Figure 4).

The role of selection bias and injuries as challenges in the talent development of youth ski racers were investigated in several research projects. However, several other aspects, such as psychological, technical and tactical factors or skills were not investigated at all. In the future, more multi-disciplinary and longitudinal studies should be performed to elaborate on profiles of successful athletes to assess the generality and specificity of expertise in alpine ski racing. Additionally, it has to be considered that most studies concentrating on the mentioned challenges in ski racing were performed in Austria; thus, the reproducibility of the findings and a possible variance that may exist across countries should be examined in future studies.

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Figure 4. Schematic representation of the previously assessed findings in the injury prevention sequence in youth (light grey) and adolescent (= adol; dark grey) ski racing (modified according to Van Mechelen et al., 1992 and Spörri et al., 2017).
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