Limb symmetry index in competitive alpine ski racers: Reference values and injury risk identification according to age-related performance levels

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Abstract

Purpose: The aims of this study were to assess differences of limb symmetry index (LSI) in strength- and coordination-related tasks between high-level, competitive, noninjured ski racers of different age-related performance levels and to prospectively assess limb differences as a possible risk factor for traumatic and overuse injury in youth ski racers.

Methods: The study (Study 1) included 285 high-level competitive ski racers (125 females, 160 males) of 3 age-related performance levels and based on the school system: 95 youth (10–14 years, secondary modern school), 107 adolescent (15–19 years, grammar school), and 83 elite athletes (20–34 years). To investigate the second aim (Study 2), 67 of the 95 youth athletes were included and any traumatic or overuse injuries were prospectively recorded over 2 seasons. All athletes performed 4 unilateral tests (strength related: one-leg counter movement jump (OL-CMJ) and one-leg isometric/isokinetic press strength test (OL-ILS); coordination related: one-leg stability test (OL-ST) and one-leg speedy jump test (OL-SJ)). The LSI was calculated by dividing the dominant leg by the nondominant leg and multiplying by 100. Kruskal-Wallis H tests and binary logistic regression analyses were conducted.

Results: There were significant differences between the LSI of the 3 age-related performance-level groups only in the strength-related tests: the OL-CMJ ($\chi^2(2, 285) = 9.09; p = 0.01$) and the OL-ILS ($\chi^2(2, 285) = 14.79; p < 0.01$). The LSI for OL-ILS was found to be a significant risk factor for traumatic injury in youth ski racers ($Wald = 7.08; p < 0.01$). No significant risk factors were found for overuse injuries.

Conclusion: Younger athletes display slightly greater LSI values only in the strength-related tests. The cut-off value of limb differences of $<10\%$ for return to sport decisions seems to be appropriate for elite athletes, but for youth and adolescent athletes it has to be critically discussed. It seems to be necessary to define thresholds based on specific performance tasks (strength vs. coordination related) rather than on generalizations, and age-related performance levels must be considered. Limb differences in unilateral leg extension strength represent a significant injury risk factor in youth ski racers.

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Keywords: Age-related performance levels; Alpine ski racing; Injury risk; Limb differences; Youth athletes

1. Introduction

Alpine ski racing is a sport with a high risk of injury. Injury rates of 36.7 injuries per 100 athletes have been reported for athletes at the World Cup level. Additionally, the injury rate at the youth level has been reported to be 0.63 traumatic injuries per athlete. While skiing, athletes must resist external loads at high velocities and counterbalance unpredictable situations during bidirectional turning phases. In this context, the importance of a high level of physical fitness has often been stated in the literature. It can be hypothesized that a preferential lateralization of the lower limb in these situations might be a critical factor for sustaining serious injuries from falling. An abnormal lower limb symmetry index (LSI), which is characterized by asymmetries between the right and left legs, is considered a strong predictor for injuries in a diverse number of sports. Additionally, not only the magnitude of an asymmetry between legs, but also the number of different asymmetrical movements
patterns when testing diverse parameters are important factors for determining increased injury risk. Consequently, ski racers with a higher limb asymmetry in a number of physical fitness parameters may be at a higher risk of injury compared with athletes with smaller limb differences.

In the context of injury prevention in youth alpine ski racing, the biological maturity status should be considered because it is well-known that growth-related factors such as immaturity contribute to overuse injuries. The risk of sustaining such overuse injuries is intensified during the adolescent growth spurt, and late-maturing athletes might be at a higher risk for both overuse and traumatic injuries, which was proven also for youth ski racers. Additionally, during periods of rapid growth, changes in body composition may increase the development of imbalances, which could lead to an increased risk of injury. In this context, chronological age has been shown to be a significant predictor of limb asymmetries in youth and adolescent athletes between the ages of 8 and 17 years, with younger athletes showing greater asymmetries compared with their older, more experienced counterparts.

In alpine ski racing, the role of lower limb asymmetries in performance-relevant physical fitness parameters has not yet been investigated. One of the most common traumatic injuries in elite ski racing is the rupture of the anterior cruciate ligament (ACL), which accounts for 13% of all injuries that occur at the World Cup level. The LSI is often used as a criterion for returning to the sport after ACL ruptures. A discrepancy in limb differences of <10% is typically used to define the cut-off for whether the athlete is ready to return to the sport. However, Myer and colleagues suggested using diverse thresholds for differing performance tasks, as, for example, a 20% threshold for jumping tasks, a 15% threshold for hip abduction, and a 10% threshold for single-limb landing tasks. In this context, it may be important to distinguish between strength- and coordination-related performance tasks when determining cut-off values for return-to-sport decisions. Although most existing studies have highlighted the importance of limb symmetry for injury prevention, it remains unclear whether the cut-off value of approximately 10% for return-to-sport decisions is appropriate. Therefore, it is critical to establish the natural range of interlimb variations of uninjured athletes of a specific cohort (i.e., alpine ski racers) at varying age-related performance levels as benchmark for decisions. Based on previous findings in other sports, it can be hypothesized that noninjured athletes may not show significant interlimb differences in performance-predictive physical fitness parameters and that the higher the level of racing performance, the lower the limb differences might be. Additionally, it seems interesting to investigate this aspect in dependence of the type of required tasks. In this context, the comparison of LSI in strength- vs. coordination-related tests should be assessed owing to the importance of both aspects in the athletic-specific training of ski racers.

Therefore, the first aim of this study (Study 1) was to assess the influence of age-related performance levels on the LSI in high-level, competitive, non-injured athletes to assess the natural range of LSI. It was hypothesized that the frequently used 10% cut-off value is not an appropriate means of identifying limb asymmetries. Additionally, as a subaim, these aspects should be compared within and between different strength- and coordination-related tasks.

As mentioned, alpine ski racing is a sport with a high risk of injury. A first study by Müller et al. assessed the modifiable and nonmodifiable athlete-related risk factors for injury in youth ski racers. The study reported that anthropometric characteristics and biological maturity status (both nonmodifiable), as well as core strength and neuromuscular control (both modifiable), were significant risk factors for injury in youth ski racers <15 years of age. The authors thus suggested assessing the role of limb dominance as a critical factor for injuries in youth ski racing. Owing to the findings that younger athletes showed more pronounced limb differences than their older counterparts in other sports, it seems especially important to assess limb differences as a possible risk factor for injury in youth ski racers between 10 and 15 years of age, because this age group is the youngest age group competing at the national level. Therefore, the secondary aim of the present study (Study 2) was to prospectively assess the role of limb differences as possible risk factor for injury in youth ski racers. It was hypothesized that athletes with higher LSI values would be at a greater risk of injury.

2. Materials and methods

2.1. Study 1

2.1.1. Participants

In total, 285 ski racers were included in the study (125 females, 160 males). To investigate the influence of age and training adaptations, all athletes were assigned to one of the following age-related performance levels: youth (including all ski racers from secondary modern school), adolescent (including all ski racers from grammar school), or elite ski racers. A total of 95 athletes (39 females, 56 males) who ranged in age from 10 to 14 years and who were students at a skiing-specific secondary modern school were classified as "youth" athletes. Another 107 athletes (47 females, 60 males) between the ages of 15 and 19 years who were students at an international skiing-specific grammar school were categorized as adolescent athletes. Athletes at both schools underwent a strict selection process. All athletes competed at high national levels, and the adolescent athletes also participated in international races. The oldest and most experienced athletes (n = 83; 39 females, 44 males) were ≥20 years of age, were members of the Austrian Skiing Federation, and participated in World Cup, European Cup, or Fédération Internationale de Ski races. These athletes were classified as elite ski racers. For this study, exclusion criteria for the establishment of limb asymmetries included an injury in the last 3 months, a lower limb surgery in the last 12 months, current infection, or other illnesses. A detailed description of all included athletes (separated into the 3 age-related performance levels) is shown in Table 1.

2.1.2. Testing procedure

The study was performed in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of the Department of Sport Science of the University of
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2.1.2.2. One-leg isometric/isokinetic press strength test (OL-ILS)

To assess the maximal isometric leg extension strength in a closed kinetic chain, 3 one-leg isometric leg extensions were performed as described by Raschner et al. This test has been shown to have good reliability values (ICC: 0.95—0.96). The test was performed in a sitting position with a knee angle of 100° (180° = fully extended knee). The greater trochanter, the lateral intercondylar notch, and the lateral malleolus were used as the landmarks to define the angle. Each athlete was instructed to maximally extend his/her leg against the plate. The absolute force (N) was registered and transmitted to a computer and the highest value of absolute force (N) of the 3 trials was considered for each leg in the analyses. As recommended by the test batteries used for diverse performance levels, the elite athletes did not perform a maximal isometric leg extension strength test, but instead they performed an isokinetic leg extension strength test. The Con-Trex linear leg press (CMV AG, Duebendorf, Switzerland) was used for closed chain testing of unilateral leg extension strength. After repeating 3 contractions at 70%—80% maximal voluntary ability, and a 1-min break, the athlete performed 6 maximal contractions for each leg. The measurements were performed in continuous passive motion at knee angles between 85° and 120° (180° = full knee extension) and a velocity setting of 0.2 m/s. The trials with the highest maximum forces (N) were used in the analyses. Reliability of this test has been previously reported by Platzer et al. (ICC: 0.94—0.97).

2.1.2.3. One-leg stability test (OL-ST)

An MFT® Challenge Disc (Trend Sport Trading GmbH, Kirchberg, Austria) was used to assess unilateral balance ability. This testing protocol has been found to have good reliability (ICC: 0.76—0.82). A detailed description can be found in Hildebrandt et al. The challenge disc was free to move in all directions and was connected to a computer positioned at eye level. The athletes were asked to maintain balance for 20 s while standing in the middle of the disc, without shoes and with their arms free to assist with balance (2 trials). Coordi software MFT Challenge Disc 2.0 (Trend Sport Trading GmbH) provided instant feedback on the current standing position (within a circle). The level of stability (index) was recorded based on the position of the body’s center of gravity within the circle. The possible range of the stability index ranges from 1 (perfect) to 5 (bad).

2.1.2.4. One-leg speedy jump test (OL-SJ)

As described by Hildebrandt et al., one-leg jump coordination was assessed using the speedy jump test. The Speedy Basic Jump Set (Trend Sport Trading GmbH) was used to create the jump coordination regimen, which consisted of 16 jumps (forward—backward—forward and sideways). The jumps had to be completed as quickly as possible while jumping on 1 leg without a rest between the hurdles. The test was considered invalid as soon as the athlete touched the ground with the nonjumping/raised leg or if he or she had direct contact with the speedy basic jump hurdles. The time(s) were measured with 2 stop watches beginning as soon as the participant started to jump and ending when he or she reached the finish line. The mean value of both stop watches was recorded.

### Table 1

| Age (year) | 11.8 | 11.8 | 11.8 | 16.1 | 16.5 | 16.3 | 21.8 | 21.2 | 21.5 |
|-----------|------|------|------|------|------|------|------|------|------|
| 39        | 56   | 95   | 47   | 60   | 107  | 39   | 44   | 83   |
| Body height (cm) | 151.0 | 150.6 | 150.8 | 164.9 | 175.6 | 170.1 | 168.9 | 180.6 | 175.1 |
| Body weight (kg)  | 42.4 | 40.5 | 41.3 | 58.8 | 74.8 | 63.7 | 67.5 | 82.2 | 75.3 |

### Anthropometric characteristics of the participants by performance level (mean ± SD)

Innsbruck. The athletes, or their parents or coaches (for youth and adolescent athletes), were informed of the study aims, procedures, and risks before written informed consent was obtained. All tests were carried out before the start of the competitive season.

Before testing, anthropometric characteristics (body height (cm) and body weight (kg)) were assessed, and the subjectively preferred dominant leg was defined. Previous literature defines the subjective dominant leg as the leg preferred when kicking a ball and when stepping on a platform. In case of differing preferred legs in these 2 situations, the athletes were asked to let themselves fall forward; the front leg that took the whole body weight was then defined as the subjective dominant leg.

The tests were carried out in a performance laboratory under standardized conditions. A standardized warm-up program was completed according to performance group. The testing procedure included the following unilateral tests.

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**Table 1**

| Age (year) | 11.8 | 11.8 | 11.8 | 16.1 | 16.5 | 16.3 | 21.8 | 21.2 | 21.5 |
|-----------|------|------|------|------|------|------|------|------|------|
| 39        | 56   | 95   | 47   | 60   | 107  | 39   | 44   | 83   |
| Body height (cm) | 151.0 | 150.6 | 150.8 | 164.9 | 175.6 | 170.1 | 168.9 | 180.6 | 175.1 |
| Body weight (kg)  | 42.4 | 40.5 | 41.3 | 58.8 | 74.8 | 63.7 | 67.5 | 82.2 | 75.3 |
and the best trial for each leg was included in the analyses. The reliability of this test has been demonstrated previously (ICC: 0.79–0.83).  

For all tests, a familiarization trial was performed before testing. To assess the influence of age-related performance level on the LSI and to assess the natural range of the LSI in uninjured ski racers (first aim of Study 1) for all tests, the trial with the best performance was selected for each leg for the LSI analyses. Based on the results of each performance test, the objectively assessed leg imbalances were defined as LSI, calculated by dividing the greater value of 1 limb (representing the dominant leg for this test) by the lower value of the other limb (representing the nondominant leg for this test) and multiplying by 100. For the tests OL-CMJ, OL-ILS. For the tests in which a lower value represented better performance (OL-ST, OL-SJ), the value of the nondominant leg was divided by the value of the dominant leg and multiplied by 100.

With respect to the subaim of Study 1 (comparison of strength- and coordination-related tests), additional analyses were performed. Based on a previous definition, the 10% criteria was chosen to descriptively describe similarities and differences between the different test tasks (strength- vs. coordination-related tasks). Limb differences of <10% were considered as symmetry between legs, whereas differences of >10% were considered as asymmetry. The 2 OL-CMJ and OL-ILS tests can be categorized as strength-related tests and the OL-ST and OL-SJ tests can be categorized as coordination-related tests. Apart from the representation of the 4 tests separately, the 2 strength-related tests and the 2 coordination-related tests were additionally analyzed as combined measures, respectively. For analyzing possible differences in symmetry and asymmetry between the 2 groups (strength- vs. coordination-related tests), the athletes were classified into 4 categories (separately by strength- and coordination-related tests): (1) symmetry in both tests, (2) asymmetry in 1 test, symmetry in the other test, (3) asymmetry in both tests toward the same leg, and (4) asymmetry in both legs but not toward the same leg.

2.1.3. Statistical analyses

All calculations were performed using IBM SPSS Version 23.0 (IBM Corp., Armonk, NY, USA). The normal distribution was tested using the Shapiro–Wilk test. The values of the dominant and nondominant legs in the 4 test modalities were normally distributed, whereas the calculated LSI values were not normally distributed.

Differences in the LSI of the 4 test modalities between the 3 age-related performance groups were tested using Kruskal-Wallis H tests as the global hypothesis test. In cases of global significance in the Kruskal-Wallis H test, Mann-Whitney U tests were used as post hoc tests to assess differences in the LSI values between 2 performance-level groups. Owing to the multiple comparisons, the chance of a rare event increases, and thus the likelihood of incorrectly rejecting a null hypothesis increases. For this reason, a Bonferroni correction was used for the Mann-Whitney U tests. The α level was adjusted by the number of performed U tests (p = 0.017 (0.05/3)), given the fact that the level of significance was set at 0.05.
91.1% of males), 86.9% of the adolescent athletes (93.0% of females; 84.3% of males), and 88.2% of the elite athletes (82.1% of females; 91.6% of males) favoring the right leg. The percentage of athletes whose right leg was the objectively measured dominant leg (better values) is presented in Fig. 1, by age-related performance level.

Test value differences in the dominant and nondominant legs are presented in Table 2 by age-related performance level. The LSI of the 4 test modalities is presented in Fig. 2 by age-related performance level. For testing the global hypothesis, the Kruskal-Wallis H test revealed significant differences between the 3 age-related performance groups for the LSI of both strength-related tests: OL-CMJ ($\chi^2(2, 285) = 9.09; p = 0.01$) and OL-ILS ($\chi^2(2, 285) = 14.79; p < 0.01$). Bonferroni corrected Mann-Whitney U tests (post hoc tests) showed significant differences in the LSI of the OL-ILS between youth and adolescent athletes ($z = -3.72; p < 0.01$) and between youth and elite athletes ($z = -2.47; p = 0.01$). Additionally, a significant difference was found in the LSI of the OL-CMJ between adolescent and elite athletes ($z = -2.97; p < 0.01$).

3.2. Study 2

3.2.1. Occurrence of traumatic and overuse injuries

Based on the database, a total of 76 injuries were recorded over the 2-season study period. A detailed description of the number of injuries, involved athletes, injury rates, and injury severities for both traumatic and overuse injuries are presented in Table 3. The body part most affected by traumatic injuries was the knee (31.1%), followed by ankle or foot (24.6%), lower leg (9.8%), and head (6.6%). The most frequently reported types of traumatic injuries were soft tissue contusions (29.5%), followed by bone fractures (26.2%), bone bruises (16.3%), and muscle strains (14.5%). In total, 2 isolated ruptures of the ACL were reported (1 male skier, 1 female skier). Most of the traumatic injuries (71.9%) occurred during training, although some occurred during leisure time activities (18.8%), and 6 traumatic injuries (9.3%) were recorded during competitions. Most of the overuse injuries affected the knee (53.3%) and were described as anterior knee pain, although lower back pain (20.0%) was also common.

3.2.2. LSI as a risk factor for injury

The multiple binary logistic model for traumatic injuries explained 20.1% of the variance among the athletes (Nagelkerke’s $R^2 = 0.201$), and 65.6% of the cases were predicted correctly. The LSI of the OL-ILS was a significant predictive risk factor for sustaining a traumatic injury in youth ski racing (Wald = 7.08; $p < 0.01$). Athletes with higher LSI values had a higher risk of traumatic injuries. There was a significant difference in the LSI of the OL-ILS between athletes with traumatic injuries and noninjured athletes ($z = -2.645; p = 0.008$). Specifically, athletes sustaining traumatic injuries had higher LSI values.

The multiple binary logistic model for overuse injuries explained 16.1% of the variance among the athletes (Nagelkerke’s $R^2 = 0.161$), with 84.4% of the cases being predicted correctly. There were no significant risk factors found
for overuse injuries. Additionally, with respect to overuse injuries, no significant differences were found for any of the LSI values between injured and noninjured athletes.

4. Discussion

Alpine ski racing is a sport with a high risk of injury, with the most common injury being ACL ruptures. The LSI is often used as the criterion for whether athletes can return to their sport after an ACL injury.22,35 Some studies suggested a cut-off value of a limb difference of <10%,23 whereas Myer et al.22 proposed using diverse thresholds for differing tasks. However, no study has yet investigated limb differences in noninjured ski racers at varying age-related performance levels to critically discuss the suggested different thresholds for diverse performance tasks. Additionally, no study has determined the limb dominances for both strength- and coordination-related tasks.

4.1. Study 1

More than 80% of the athletes in the present study displayed subjective right-leg dominance. However, the findings showed that differences in the dominance of the right and the left leg can be observed in strength-related and coordination-related tasks. A slight right-leg dominance was found for the OL-ILS and OL-SJ and a slight left-leg dominance was found for the OL-ST test in the adolescent athletes. Even though in most tests the athletes performed better with their right leg, these findings provide further support that limb differences, when averaged across groups, should be calculated based on limb dominance rather than left and right legs to avoid nullifying differences, a finding also reported by Jones and Bampoukas36 and Newton et al.37

Although alpine ski racing is a symmetrical sport, which leads to the assumption that no limb dominances should be present,12 all 3 noninjured groups showed differences between their dominant and nondominant legs for all 4 test modalities. The greatest differences between dominant and nondominant leg were found in the OL-CMJ in all 3 age-related performance levels. The OL-CMJ test is a measure of explosive lower limb strength, which is a critical component of ski racing. The greater limb dominance in the OL-CMJ test suggests that athletes may be using their dominant leg more aggressively, which could increase the risk of injury.

Table 3

| Occurrence of traumatic and overuse injuries |
|---------------------------------------------|
|                                             |
| Injuriesa                                    |
| Traumatic injuries                          | 61 (80.3) | 15 (19.7) |
| Overuse injuries                            | 42 (57.1) | 24 (32.9) |
| Total                                       | 103 (100) | 40 (100)  |

aData are presented as n (%); bData are presented as %.
performance groups (10.4%–14.8%). This finding is comparable with results reported by Lockie et al.,38 who found mean limb differences of 10.4% in CMJ jumping height in team sport athletes. Likewise, Stephens et al.39 investigated bilateral differences in single-leg countermovement jumps in healthy athletes and stated that limb symmetry in this test is the exception rather than the norm. The greater difference in the OL-CMJ, compared with the other 3 tests, may be explained by the fact that one-leg jumping is a very complex movement that requires a large amount of power combined with well-developed intra-limb coordination.

The previously recommended threshold of 10% for limb differences23 needs to be questioned for all test modalities with respect to the LSI because in the OL-ST and the OL-CMJ, all age-related performance groups showed slightly higher LSI values than 110% (OL-ST: 111.3%–113.8%; OL-CMJ: 110.4%–114.8%). This suggests that differences between limbs were greater than 10%. Myer et al.22 suggested using a 20% threshold for jumping tasks, which seems to be too high for ski racers because, in all 3 age-related performance groups, an LSI of <115% was found. However, the higher the performance level, the smaller the observed limb differences were. Elite athletes had LSI values of 110.4 ± 10.7 (OL-CMJ) and 111.3 ± 8.9 (OL-ST), mean ± SD. Therefore, a threshold of limb differences of <10% might be reconsidered for elite athletes returning to sport after injury, even though tests assessing unilateral balance ability and OL-CMJ should be interpreted with caution. Based on the present study, limb differences of slightly >10% should be accepted for elite athletes. The smallest imbalances were found for the OL-SI, the most complex test in terms of intermuscular coordination. A high degree of motor control is necessary for these tests, which might be transferable to sport-specific requirements in alpine ski racing. However, it should be considered that all athletes, independent of performance level, were familiar with the OL-SI. When comparing the results of this study to norm data for healthy nonathletes of the same ages,26 the athletes in the present study performed very well. The findings of the present study suggest that using a battery of tests, including strength- and coordination-related tasks, is more reliable for return-to-sport-decisions than performing only a single test. Nevertheless, thresholds should be related to performance tasks, including different motor abilities rather than generalized tests, which was suggested also by Myer et al.22 The present results indicate that thresholds might be defined for strength- and coordination-related tasks separately. Additionally, it can be concluded that different thresholds should be used for elite and youth/adolescent athletes only in the strength-related tests because of the significant differences, whereas in the coordination-related tests the same cut-off values could be used. However, it has to be considered that identifying athletes at high risk for injury—independent of whether the athlete returns to sport after injury or if he or she is noninjured—is always difficult.30 The suggested cut-off values should only represent reference values and should not be used to decide if an athlete is ready to return to sport after injury.

Additionally, in line with previous studies,21 differences were found in the strength-oriented LSI for OL-CMJ and the OL-ILS between the 3 age-related performance groups. Younger and less experienced athletes displayed slightly greater LSI values, meaning they had more distinctive limb differences; however, differences were only found in the strength-oriented tests. The results of the present study might indicate that unilateral strength-oriented tests, including the evaluation of LSI, may be more useful for distinguishing between diverse performance levels than are coordination-related tests. It is possible that sport-specific training plays a role in adaptations of muscle strength. Elite athletes have more hours of strength training in which exercises such as squats are important, whereas strength training in youth athletes focuses primarily on coordination- and stabilization-oriented strength training and core strength training, instead of on maximal strength training.9 The finding of the current study that the LSI of the OL-ILS represented a significant risk factor for injury in youth athletes supports this hypothesis. Additionally, Atkins et al.41 showed that bilateral imbalances are most distinctive at the post-peak height velocity age range, owing to the nonlinear maturation of the neuronal system and changes in single movements. This finding could then explain the differences observed between youth and elite athletes as well as those between adolescent and elite athletes in the present study. Moreover, a previous study of soccer players42 found that strength asymmetries were related to age and practice time. Older players had lower force asymmetries, which agrees with the results of the present study. Fousekis et al.32 explained that less experienced players had a higher prevalence of force asymmetries, which might be associated with their decreased capacity to deal with preexisting asymmetries from incomplete development of neuromuscular patterns.42 In contrast, no significant differences were found in the coordination-related tests (OL-ST and OL-SJ) between the 3 age-related performance groups. It can thus be assumed that imbalances in tasks that require high neuromuscular control are not a result of sport-specific training. The results of the present study emphasize the necessity to differentiate between performance levels when using the LSI considerations to make return-to-sport decisions for alpine ski racing.

Another important consideration is the influence of muscle fatigue on changes in LSI, which has been proposed by Leister et al.32 In alpine ski racing, the high activity of the leg muscles and the resistance to external forces result in fatigue by the end of a race. However, the role of muscle fatigue and its consequences for LSI in performance-related parameters have not yet been investigated in alpine ski racing. However, muscle fatigue should be considered when making return-to-sport decisions after ACL injuries because it is possible that greater limb asymmetries could exist in a fatigued state, which would likely lead to a greater risk for injury. Future studies should address this aspect.

For a more detailed descriptive analysis with respect to asymmetries/symmetries, the athletes were classified into 4 categories (symmetry in both tests, asymmetry in 1 test, asymmetry in both tests toward the same leg, asymmetry in both
tests toward different legs) by combining the values for both strength-related tests and both coordination-related tests. Interestingly, in the strength-related tests most youth (54.7%) and adolescent athletes (46.7%) had 1 asymmetry, meaning a limb difference of >10%, whereas approximately one-third of these athletes represented symmetry in both strength-related tests (30% and 38%, respectively). Among the elite athletes, >50% did not show an asymmetry, and approximately 40% had 1 asymmetry. In the coordination-related tests, a very similar picture was found for all 3 age-related performance groups: nearly one-half of the athletes had symmetry in both tests and half of the athletes had 1 asymmetry. In the strength-oriented tests, approximately 10% of the youth and adolescent athletes displayed asymmetry in both tests toward the same leg, a finding that shows a clear indication of asymmetry. However, a longitudinal prospective study should be performed to investigate whether these athletes with clear indication of asymmetry are indeed at a greater risk for injury. In the coordination-related tests, hardly any athletes showed asymmetries in both tests.

4.2. Study 2

4.2.1. Occurrence of traumatic and overuse injuries

Although an epidemiologic classification of traumatic and overuse injuries in elite youth athletes was not an explicit aim of the current study, a comprehensive discussion and comparison with previous studies is useful at this point. The results of the present study show that most injuries were traumatic injuries (82.4%). The traumatic injury rate per athlete was comparable with previous rates found in youth and adolescent ski racing. Fort-Vanmeerehaeghe et al. argued that prepubescent athletes may be at a lower risk of injury because they have a lower body mass, have shorter joint lever arms, and do not generate as much of a dynamic valgus load as their more mature counterparts. In line with previous studies, the knee was the most commonly injured body part in the present study, where it accounted for 31.1% of injuries. In previous studies, it accounted for 36.5% of injuries at the youth level, 41% at the adolescent level, and 35.6% at the elite level.

Similar to a previous study at the youth level (where 1 ACL rupture in a male athlete was reported), ACL ruptures in the present study did not represent a frequently reported injury (1 ACL rupture each in 1 male and 1 female athlete). However, other studies have reported a high incidence of ACL ruptures at the adolescent and elite levels. It is possible that the elastic properties of tendon structures in the growing athlete are greater and thus are more pliant than in full-grown athletes. Most of the traumatic injuries (31.2%) in the present study were classified as moderate injuries, which is in line with other studies at the youth (44.2%) and the adolescent (46%) levels. However, it has been reported that at the elite level most traumatic injuries are classified as severe (35.6%).

A possible explanation for the differences between youth/adolescent and elite athletes is that youth and adolescent athletes do not reach the high velocities that elite athletes do and thus may not experience the dangerous situations that lead to severe falls. In the present study, most of the traumatic injuries were soft tissue contusions (29.5%), followed by bone fractures (26.2%), whereas in a previous study at the youth level, bone fractures occurred more frequently (46%).

At the elite and adolescent levels, overuse injuries represent a serious medical problem in alpine ski racing. At the elite level, more than one-third of all top 40 ranked athletes in the Slalom World Cup reported problems with low back pain. Additionally, at the adolescent level, >50% of athletes had ≥1 overuse injury in a 2-season study period. However, despite the fact that high training volumes, overscheduling, and the adolescent growth spurt are all risk factors for overuse injuries, a low prevalence of overuse injuries was found in the present study. At the youth level, overuse injuries are not that common, as the results of both the present study and a study by Müller et al. have shown. In line with the study by Müller et al., the knee was the most commonly affected body part for overuse injuries. Interestingly, most of the overuse injuries among youths in the present study (46.7%) caused a training time loss of <8 days. This finding may be explained by the fact that most overuse injuries were defined as idiopathic anterior knee pain, which is a general problem in growing athletes.

4.2.2. LSI as a risk factor for injuries

The second aim of the present study was to elucidate LSI as a possible risk factor for injury in youth ski racing, because this issue has not yet been investigated in this sport. For this reason, the traumatic and overuse injuries of the athletes were recorded prospectively for 2 seasons after the measurements of their LSI values. Because alpine skiing is a symmetrical sport and bidirectional turns are required, alpine ski racers generally need to have a high level of physical fitness that includes a high strength capacity in both limbs. As previous studies in other sports have revealed, athletes showing asymmetrical movements during functional movement screening tests were more likely to sustain an injury. It is possible that limb differences in strength-related tasks may also indicate a higher risk of injury for alpine ski racing. The LSI of the isometric leg extension strength test was found to be a significant risk factor for traumatic injury. Athletes with a higher LSI value were at a higher risk of injury. A significant difference was also found in the LSI of the OL-ILS between injured and noninjured athletes. This finding emphasizes the importance of having a well-developed, symmetrical strength capacity in both legs starting at an early age. Interestingly, when considering the results of Study 1, the greatest differences in the LSI between the youth and the adolescent athletes as well as between youth and elite athletes were found in the OL-ILS. Consequently, it is possible that limb differences in extension strength may be more pronounced in youth athletes during phases of rapid growth. Therefore, regular fitness testing of young athletes is crucial in detecting strength imbalances. Based on the results of regular fitness testing, measures can be taken to balance the differences to help prevent possible injuries. However, the regression analysis in the present study explained only 24% of the LSI risk factor among the athletes.
Thus, more than three-fourths of the variance of the athletes is not yet accounted for when considering LSI only, and previously assessed risk factors for injury (core strength, neuromuscular control, anthropometric characteristics, biological maturity status) may therefore play a role.

The assessed LSI parameters did not represent significant risk factors for overuse injuries. However, the very small rate of overuse injuries limits the data analysis in the present study. Future studies with a larger sample size and a longer intervention period should be performed. Sufficient core strength has a positive effect on preventing overuse injuries, which was not considered in the present study. Therefore, it can only be hypothesized that lower limb asymmetries are more relevant to traumatic injuries but not to overuse injuries. It is possible that, owing to the less developed and less stable skiing technique in youth athletes compared with adolescent and elite athletes, youth athletes may be at a higher risk for injuries that occur because of technical mistakes, as, for example, ACL ruptures based on slip catch or dynamic snow plow mechanisms. In such situations, and perhaps also owing to less well-prepared slopes in youth races, it is possible that limb differences in strength capacities may lead to traumatic injuries. Thus, in addition to training that focuses on the development of a stable skiing technique, training for youth athletes should concentrate on the individual neuronal and physical development of young ski racers to detect and prevent asymmetries. Additionally, as is done in youth soccer, unilateral drills should be implemented in the training process of young athletes to maximize (neuronal) adaptations.

5. Conclusion

The present study supports the use of unilateral performance tests to detect lower limb asymmetries, allowing coaches to design individual programs for each athlete. To calculate limb differences, coaches should refer to limb dominance rather than left and right leg dominance to avoid nullifying differences. The often-discussed thresholds of limb differences in the context of returning to sport after injuries should be defined separately for strength- and coordination-related tasks. Moreover, the cut-off values should be defined separately for age-related performance-level groups for the strength-related tests. Additionally, differences in the LSI between the 3 age-related performance groups were only found in the strength-related tests OL-CMJ and OL-ILS. Thus, unilateral strength-oriented tests, including the evaluation of LSI, may be more useful in distinguishing between diverse performance levels compared with coordination-related tasks.

Results of the present study revealed that unilateral leg extension strength represents a significant risk factor for traumatic injuries in youth ski racers. Especially in sports, where bilateral requirements are typical, coaches are advised to develop a symmetrical strength capacity in both legs starting at an early age.

Injured athletes displayed greater LSI values in the OL-LSI than noninjured athletes. However, these findings can only be interpreted as a tendency, and a prospective study including more athletes and a longer intervention period should be performed in the future. The greatest differences between the 3 age-related performance groups in Study 1 were found in the OL-LSI, which indicates that limb differences in leg extension strength may be more pronounced in youth athletes during phases of rapid growth, as shown in other studies. The findings of the study provide potential cut-off values for limb asymmetries according to age and type of performance testing.

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Authors’ contributions

LSM is the guarantor of the study, collected the data, did the performance testing, performed literature search and statistical analyses, interpreted the data, and prepared the manuscript; CH collected the data and did the performance testing, performed literature search and statistical analyses, interpreted the data, and helped draft the manuscript; CF interpreted data, provided sports medical information, and helped draft the manuscript; CR collected the data, did the performance testing, participated in the design and coordination, and helped draft the manuscript. All authors approved the final version of the manuscript, and agree with the order of presentation of the authors.

Competing interests

The authors declare that they have no competing interests.

References

1. Spoerri J, Kroll J, Gilgen M, Muller E. How to prevent injuries in alpine ski racing: what do we know and where do we go from here? Sports Med 2017;47:599–614.
2. Florenes TW, Bere T, Nordsletten L, Heir S, Bahr R. Injuries among male and female World Cup alpine skiers. Br J Sports Med 2009;43:973–8.
3. Bere T, Florenes TW, Nordsletten L, Bahr R. Sex differences in the risk of injury in World Cup alpine skiers: a 6-year cohort study. Br J Sports Med 2013;48:36–40.
4. Muller L, Hildebrandt C, Muller E, Oberhoffer R, Raschner C. Injuries and illnesses in a cohort of elite youth alpine ski racers and the influence of biological maturity and relative age: a two-season prospective study. Open Acc J Sports Med 2017;8:22.
5. Hintermeister RA, O’Connor DD, Dillmann CJ, Suplizio CL, Lange GW, Steadman JR. Muscle activity in slalom and giant slalom skiing. Med Sci Sports Exerc 1995;27:315–22.
6. Berg HE, Eiken O, Tesch PA. Involvement of eccentric muscle actions in giant slalom racing. Med Sci Sports Exerc 1995;27:1660–70.
7. Kroll J, Sporri J, Kandler C, Fasel B, Muller E, Schwameder H. Kinetic and kinematic comparison of alpine ski racing disciplines as a base for specific conditioning regimes. In: Colloud F, Domalain M, Monnet T, editors. 33rd International Conference on Biomechanics in Sports. Poitiers, France; 2015. p. 816–9.
8. Kroll J, Sporri J, Fasel B, Muller E, Schwameder H. Type of muscle control in elite alpine skiing — is it still the same than in 1995? In: Muller E,
26. Hildebrandt C, Müller L, Hildebrandt C. Traumatic and overuse injuries among elite alpine skiers: A comparative study. Br J Sports Med 2017;51:1553–8.
27. Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK, Robertson M, et al. Determination of functional strength imbalance of the lower extremities. J Strength Cond Res 2006;20:971–7.
28. Lockie RG, Callaghan SJ, Berry SP, Cooke ERA, Jordan CA, Robertson M, et al. Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. J Strength Cond Res 2014;28:3557–66.
29. Stephens TM, Lawson BR, DeVoe DE, Reiser RF. Gender and bilateral differences in single-leg countermovement jump performance with comparison to a double-leg jump. J Appl Biomech 2007;23:190–202.
30. Bahr R. Why screening tests to predict injury do not work—and probably never will. . .: a critical review. Br J Sports Med 2016;50:776–80.
31. Atkins SJ, Bentley I, Hurst HT, Sinclair JK, Robertson M, et al. Current performance testing trends in junior and elite Austrian alpine ski, snowboard and ski cross racers. Orthop Traumatol Sport Traumatol Arthrosc 2013;8:193–202.
32. Platzer HP, Raschner C, Patterson C, Lembert S. Comparison of physical characteristics and performance among elite snowboarders. J Strength Cond Res 2009;23:1427–32.
33. Brooks JH, Fuller CW. The influence of methodological issues on the results and conclusions from epidemiological studies of sports injuries: illustrative examples. Sports Med 2006;36:459–72.
34. Clarsen B, Myklebus G, Bahr R. Development and validation of a new method for the registration of overuse injuries in sports injury epidemiology. Br J Sports Med 2013;47:495–502.
35. Ihuthumb MP, Altenburger AR, Staci T, Hewett TE, Paterno MV, Schmitt LC. Young athletes after ACL reconstruction with quadriceps strength asymmetry at the time of return-to-sport demonstrate decreased knee function 1 year later. Knee Surg Sports Traumatol Arthrosc 2018;26:426–33.
36. Jones PA, Bampouras TM. A comparison of isokinetic and functional methods of assessing bilateral strength imbalance. J Strength Cond Res 2010;24:1553–8.
37. Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK, Robertson M, et al. Determination of functional strength imbalance of the lower extremities. J Strength Cond Res 2006;20:971–7.
38. Lockie RG, Callaghan SJ, Berry SP, Cooke ERA, Jordan CA, Robertson M, et al. Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. J Strength Cond Res 2014;28:3557–66.
39. Stephens TM, Lawson BR, DeVoe DE, Reiser RF. Gender and bilateral differences in single-leg countermovement jump performance with comparison to a double-leg jump. J Appl Biomech 2007;23:190–202.
40. Bahr R. Why screening tests to predict injury do not work—and probably never will. . .: a critical review. Br J Sports Med 2016;50:776–80.
41. Atkins SJ, Bentley I, Hurst HT, Sinclair JK, Hesketh C. The presence of bilateral imbalance of the lower limbs in elite youth soccer players of different ages. J Strength Cond Res 2013;30:1007–13.
42. Fousekis K, Tsepis E, Vagenas G. Lower limb strength in professional soccer players: profile, asymmetry, and training age. J Sports Sci Med 2010;9:364–73.
43. Leister I, Mattiaisch G, Kindermann H, Ortmairer R, Barthofer J, Vassary I, et al. Reference values for fatigued versus non-fatigued limb symmetry index measured by a newly designed single-leg hop test battery in healthy subjects: a pilot study. Sports Sci Health 2018;14:105–13.
44. Floreses TW, Nordsletten L, Heir S, Bahr R. Injuries among World Cup ski and snowboard athletes. Scand J Med Sci Sports 2012;22:58–66.
45. Hildebrandt C, Raschner C. Traumatic and overuse injuries among elite adolescent alpine skiers: a two-year retrospective analysis. Int Sport Med J 2013;14:245–55.
46. Kubo K, Kanchisa H, Kawakami Y, Fukunaga T. Growth changes in the elastic properties of human tendon structures. Int J Sports Med 2001;22:138–43.
47. Jahnle R, Spori J, Kröll J, Müller L. Prevalence of overuse problems in World Cup alpine skiers – an explorative approach. In: Müller E, Kröll J, Lindinger S, Pfusterschmied J, Stögg L, editors. Science and skiing VI: book of abstracts. Salzburg: University of Salzburg; 2013. p. 143.
48. Patel DR, Villalobos A. Evaluation and management of knee pain in young athletes: overuse injuries of the knee. Trans Pediatr 2017;6:190–8.
49. Rejeb A, Johnson A, Vaeyens R, Horobeau C, Farooq A, Witvrouw E. Compelling overuse injury incidence in youth multisport athletes. *Eur J Sport Sci* 2017;17:495–502.

50. Jordan MJ, Aagaard P, Herzog W. Anterior cruciate ligament injury/reinjury in alpine ski racing: a narrative review. *Open Acc J Sports Med* 2017;8:71–83.

51. Spörri J, Kröll J, Haid C, Fasel B, Müller E. Potential mechanisms leading to overuse injuries of the back in alpine ski racing: a descriptive biomechanical study. *Am J Sports Med* 2015;43:2042–8.

52. Bere T, Florenes TW, Krosshaug T, Nordsletten L, Bahr R. Events leading to anterior cruciate ligament injury in World Cup alpine skiing: a systematic video analysis of 20 cases. *Br J Sports Med* 2011;45:1294–302.

53. Ramirez-Campillo R, Sanchez-Sanchez J, Gonzalo-Skok O, Rodriguez-Fernandez A, Carretero M, Nakamura FY. Specific changes in young soccer player’s fitness after traditional bilateral vs. unilateral combined strength and plyometric training. *Front Physiol* 2018;9:265. doi:10.3389/fphys.2018.00265.