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Publication date:
2020-09

Permanent link:
https://doi.org/10.3929/ethz-b-000425391

Originally published in:
Physical Therapy in Sport 45, https://doi.org/10.1016/j.ptsp.2020.05.013

Physical Therapy in Sport 45 (2020) 56–62

Contents lists available at ScienceDirect

Physical Therapy in Sport

journal homepage: www.elsevier.com/ptsp

Original Research

Biomechanical quantification of deadbug bridging performance in competitive alpine skiers: Reliability, reference values, and associations with skiing performance and back overuse complaints

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ARTICLE INFO

Article history:
Received 11 March 2020
Received in revised form
23 May 2020
Accepted 25 May 2020

Keywords:
Stabilization
Athletes
Biological maturity
Performance
Injury

ABSTRACT

Objectives: (1) To study the reliability of quantifying rear-chain stabilization capacity during deadbug bridging (*DBB*), (2) to provide reference values for competitive alpine skiers, and (3) to study associations with age, anthropometrics, maturation, skiing performance and back overuse complaints.
Design: Cross-sectional.
Setting: Biomechanical field experiment including questionnaires.
Participants: 12 healthy subjects (reliability experiment); 133 skiers of the *U16* category and 38 of the *elite* category (main experiment).
Main outcome measures: *DBB* performance was quantified using 3D motion capture as the maximum amplitude of the relative vertical displacement of two pelvis markers ($DBB_{displacement}$). Additionally, in U16 skiers, age, anthropometrics, maturation, skiing performance, and back overuse complaints were assessed.
Results: The reliability experiment revealed an ICC(3,1) and 95% CI of 0.81 [0.61, 0.93]. Within-subject SEM was 3.89 mm [3.16 mm, 5.12 mm]. Depending on sex and category, medians of $DBB_{displacement}$ in skiers ranged between 29 mm and 45 mm. $DBB_{displacement}$ differed between elite and U16 skiers ($p < 0.001$), but not between sexes. In U16 skiers, $DBB_{displacement}$ was independent of age, anthropometrics, and biological maturation, however, associated with skiing performance and back overuse complaints ($p < 0.05$).
Conclusion: The proposed approach may be considered an adequate method to quantify athletes' rear-chain stabilization capacity.

1. Introduction

In competitive alpine skiing, the demands on athletes' physical fitness are high (Gilgien, Kröll, Spörri, Crivelli, & Müller, 2018; Kröll, Spörri, Kandler, Fasel, & Müller, 2015). Specifically, the cyclic changes of direction and ski-snow-interaction induced perturbations of the dynamic equilibrium (Reid, Haugen, Gilgien, Kipp, & Smith, 2020), require adequate force transmission and superior stabilization capacities. On the one hand, inadequate force transmission and poor stability may reduce overall performance, e.g. by decreasing movement precision and performance consistency (Supej & Cernigoj, 2006). On the other hand, adequate force transmission and superior stability may be relevant for injury prevention, e.g. by bearing the adverse loading patterns of the spine while skiing or reducing the risk of ACL injury inciting out-of-balance situations (Bere et al., 2011; Spörri, Kröll, Haid, Fasel, & Müller, 2015). But also for athletes of other sports and non-

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https://doi.org/10.1016/j.ptsp.2020.05.013

athletic subjects, evidence for a direct relationship between insufficient stabilization capacity and musculoskeletal overuse complaints/traumatic injuries, exists (Hodges & Richardson, 1996; Kankaanpaa, Taimela, Laaksonen, Hanninen, & Airaksinen, 1998; Panjabi, 2003; Zazulak, Hewett, Reeves, Goldberg, & Cholewicki, 2007).

The ability to control the position and motion of the trunk and to allow optimal production and transfer of forces to the distal segments of the kinetic chain, is commonly called "core stability" (Kibler, Press, & Sciascia, 2006). However, an objective, reliable and valid quantification of core stability is challenging (Hibbs, Thompson, French, Wrigley, & Spears, 2008), and a variety of definitions exists (Huxel Bliven & Anderson, 2013; Willson, Dougherty, Ireland, & Davis, 2005; Wirth et al., 2017). Disagreement especially prevails on which anatomical structures should be assigned to the "core" (Hibbs et al., 2008). A more holistic approach to overcome such limitations and debates, however, is the quantification of athletes' rear-chain stabilization capacity, which plays a central role in many sports, and especially in alpine skiers. The characteristic movement and loading patterns in competitive alpine skiing not only require high stabilization capacities of the paraspinal muscles, but also those of the entire rear chain (including the posterior trunk, pelvic gridle and leg muscles). To this end, we propose a novel biomechanical approach to quantify athletes' rear-chain stabilization capacity during deadbug bridging *(DBB)* that is further described in the methods section.

As for any new physical performance test, the criteria of sufficient objectivity, test-retest reliability and (criterion, content-related and construct) validity must be given in order to be sports practically and clinically relevant. Moreover, sport-, age and sex-specific reference values need to be established. Finally, when being applied to youth athletes the fundamental changes related to ageing, height growth and biological maturation during puberty may strongly challenge the underlying test protocols, why relations between the newly suggested *DBB* performance test outcome measures and potential cofounding factors need to be investigated. Accordingly, the objectives of this study were: (1) to introduce a novel biomechanical approach for quantifying athletes' rear chain stabilization performance during *DBB* and to assess its test-retest reliability; (2) to describe *DBB* performance in two distinct populations (i.e. female and male competitive alpine skiers of the U16 category and competitive alpine skiers of the elite category) with respect to sex; and (3) to investigate the association between *DBB* performance, age, anthropometrics, biological maturation, skiing performance and the occurrence of back overuse complaints in U16 skiers undergoing phases of rapid musculoskeletal growth.

2. Materials and methods

2.1. Reporting

For reporting we followed the STROBE statement and checklist for cross-sectional studies (von Elm et al., 2007).

2.2. Study design, setting and participants

2.2.1. Reliability experiment

The reliability experiment was designed as a cross-sectional biomechanical in-field study. To verify the test-retest reliability of the proposed approach to quantify athletes' rear chain stabilization performance during DBB, hereinafter called *DBB* performance, 12 healthy subjects (seven females and five males) completed a *DBB* performance test five times on the same day. Subjects were recruited by public tender before the experiment. They were eligible if they were between 18 and 40 years of age and physically active (more than one time intense physical activity per week or more than 30 min of moderate activity per day). None of the interested subjects met the exclusion criteria of BMI larger then 45, or reduced load tolerance, which is why there were no study exclusions.

2.2.2. Main experiment

Within a cross-sectional biomechanical field experiment a total of 171 athletes, comprising 133 competitive alpine skiers of the U16 category (49 females and 84 males), hereafter called under U16 skiers, and 38 competitive alpine skiers of the elite category (19 females and 19 males), hereafter called under elite skiers, were tested for their stabilization performance during *DBB*. The tests of U16 skiers were accompanied by an assessment of age, anthropometrics, biological maturity status, skiing performance, and the prospectively surveyed occurrence of back overuse complaints as further described below. Study participation was voluntary and subjects were recruited by tender within the athlete development structures of the Swiss Ski Association (Swiss-Ski). Athletes were eligible for participating when being part of an official national U16 or elite athlete development program. None of the interested athletes met the exclusion criteria of being on the way of back-to-sports after an injury or suffering from systemic pathologies such as inflammatory arthritis or diabetes mellitus. Thus, there were no study exclusions.

Ethical approval

Participants of both experiments received detailed information provided written informed consent before participating in the study. An institutional review committee and local ethics committee (KEK-ZH-NR: 2017–01395) approved the study that is in conformity with the Helsinki Declaration and national laws.

2.3. DBB performance assessment

Athletes' rear-chain stabilization capacity was quantified as the stabilization performance during *DBB* (see VIDEO provided as supplemental online material). The underlying low dynamic exercise is executed in a closed kinematic chain with, compared to conventional open kinematic chain exercises such as trunk movements during one-leg stance or trunk tests in combination with sudden force release (Kibler et al., 2006; Radebold, Cholewicki, Polzhofer, & Greene, 2001), restricted degrees of freedom. This may promote the recruitment and neuromuscular coordination of stabilising muscles while better limiting evasive movements. The diagonal foot lift during *DBB* thereby requires a superior control of lateral bending and torsion in the trunk; two important components of mechanisms leading to back overuse injuries in alpine ski racing (Spörri et al., 2015).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.ptsp.2020.05.013

For the biomechanical quantification of the stabilization performance during *DBB*, four reflective skin markers were attached to the right and left anterior superior iliac spine and both lateral malleoli, and were recorded by an optoelectronic 3D motion capture system (Vicon, Oxford Metrics, UK) operating at 200 Hz. The initial position of *DBB* was a supine position on the floor with the arms abducted 90° from the body and the palms facing upwards (Fig. 1a). The legs were abducted such that the heels were in line with the elbows. The athletes were then instructed to lift their hip, keeping their shoulders and heels on the floor. They then had to release one heel from the ground, bend their hip and knee 90° and hold this position for 3 s (Fig. 1b). The leg was afterwards returned to the starting position as controlled as possible before the movement was repeated. Three repetitions were completed, without the

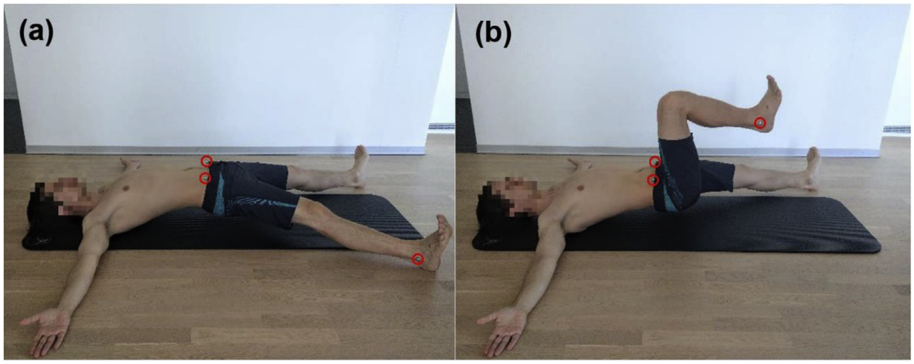


Fig. 1. Deadbug bridging (*DBB*) in (a) the initial position and (b) the leg lift phase. Participants repeated this sequence three times without their hip touching the ground. Markers are framed for clarification. The left malleolus marker is obstructed.

hips touching the ground. Trials were repeated if (i) the hip touched the ground (ii) the initial position between the attempts was not taken correctly (iii) markers were not visible due to hip flexion.

After the marker trajectories were identified with the Vicon Nexus software (Vicon Nexus v2.7, Oxford Metrics; UK) data was exported to Matlab (Matlab R2016b, The MathWorks, Inc, Natrick, MA) for subsequent calculations with customized scripts. Marker losses during recording were interpolated up to 10 frames (0.05 s). Each trial was cut into three repetitions based on the minimal vertical position of the lateral malleolus marker of the lifted leg, which in turn corresponds to the initial *DBB* position. $DBB_{displacement}$ was then calculated as the maximum amplitude of the vertical displacement (in mm) of the two pelvis markers, with the marker of the stabilising side representing the reference marker.

2.4. Age, anthropometrics and biological maturation

All U16 skiers were assessed for *body height* and *sitting height,* i.e. body height when sitting on a box minus box height (0.5 cm increments, determined by measuring tape), and *body weight* (0.1 kg increments, Seca, Hamburg, Germany). *Age* was taken at the time of the main experiment. Based on these measures, sub-ischial leg length was computed. Biological maturity status was calculated by the non-invasive method developed by Mirwald, Baxter-Jones, Bailey, and Beunen (2002). This formula estimates individual *maturity offset* of athletes, a time before or after their *peak height velocity (PHV)*. To obtain *age at peak height velocity (APHV)*, *maturity offset* is subtracted from *age*. The formula has previously been validated for competitive alpine skiers (Müller, Müller, Hildebrandt, Kapelari, & Raschner, 2015).

2.5. Skiing performance

The *skiing performance* of all U16 skiers was quantified as their performance points according to the Swiss national ranking list, where lower points indicate better performance. Points were systematically calculated based on the performance level of the starting field and skiers' time loss within their two best competitions over the previous 12 months. Further information on the corresponding point system and the Swiss national ranking list can be accessed online at https://www.swiss-ski-kwo.ch/.

2.6. Surveillance of back overuse complaints

Over a period of 12 months preceding the main experiment and at two-week intervals, all U16 skiers completed an online survey based on the Oslo Sports Trauma Research Centre (OSTRC) questionnaire on health problems (Clarsen, Ronsen, Myklebust, Florenes, & Bahr, 2014). For that purpose, every second Monday athletes received an individual web-link to a secured database (REDCap, Vanderbilt University, USA). In case of non-completion, athletes received a reminder two and three days after distribution. All responses had to be submitted within 7 days since receiving the weblink. To confirm the correctness and completeness of the entries and to ensure the quality of the OSTRC questionnaire-based data, at the end of the observation period all athletes underwent a supplemental interview and physical examination by a sports physician.

Back overuse complaints were any back pain episodes suffered during the observation period and indicated in one of the two weekly OSTRC questionnaires. In the framework of the further data analysis, all back overuse complaints were subclassified into substantial vs. non-substantial complaints based on their OSTRC severity-score. As defined by Clarsen et al. (2014), back overuse complaints were considered being "substantial" if resulting in "moderate or severe reductions in training volume", or "moderate or severe reductions in sports performance", or "complete inability to participate in sport" (i.e. athletes provided the answer 3, 4 or 5 either in question 2 or 3 of the OSTRC questionnaire). Finally, an athlete was considered "symptomatic" if he reported at least one substantial back overuse-related health problem within the 12 months prior to testing.

2.7. Statistical analysis

2.7.1. Reliability experiment

For assessing the test-retest reliability of the biomechanical quantification of $DBB_{displacement}$, we strictly followed the recommendations of Hopkins (2000) and used the consecutive pairwise spreadsheet provided by Hopkins (2015) that considers the factor of habituation that is typical in performance testing. For all calculations, data of the right leg and five trials performed on the same day were used. First, for each of the five repetitions, the $DBB_{displacement}$ mean ± SD of all participants were calculated, and repetition differences on a group level were tested for significance using a repeated measures ANOVA ($p < 0.05$). Second, the intra-class correlation coefficient ICC(3,1) was calculated, where "3" indicates the type of ICC with subjects as a random effect and trials as a fixed effect, and "1" refers to the reliability of single repeated measurements (not the average of several measurements) Hopkins (2015). It represents the intraclass correlation between the pairs of measurements in any two trials of the five repeated trials assessed, where all subjects have the same trials. ICC values were classified based on the definitions of Koo and Li (2016) (less than 0.5 indicates *poor* reliability; 0.5 to 0.75 indicates *moderate* reliability; 0.75 to 0.9 indicates *good* reliability; and greater than 0.9 indicates *excellent* reliability). Second, within-subject standard error of measurement (SEM) and within-subject standardized SEM, called 'standardized typical error', were calculated (Hopkins, 2015). Standardized typical error values were doubled before interpreting their magnitude in relation to the common thresholds of 0.2 (*small*), 0.6 (*moderate*), 1.2 (*large*), 2.0 (*very large*), 4.0 (*extremely large*) (Smith & Hopkins, 2011).

2.7.2. Main experiment

Statistical analysis was performed in *IBM SPSS* statistics software version 23. First, all metric data was checked for normality of distribution using the Kolmogorow-Smirnow (KS) test, graphical techniques and shape parameters (i.e. skewness and kurtosis coefficients) (Razali, 2011). For normally distributed data, standard parametric tests were applied. For cases, in which the KS test revealed significant results ($p < 0.05$), but corresponding skewness and kurtosis values were below the normality reference boundaries of <2.0 and < 7.0 as defined by West, Finch, and Curran (1995), statistical tests were backed-up by bias corrected accelerated (BCa) bootstrapping with 10′000 samples. Beyond these boundaries, non-parametric tests were used.

Participants' *age, maturity offset, body height, and body weight* were reported as mean ± SD, and were tested for significant sex and level group (U16 vs. elite skiers) differences using a multivariate analysis of variance (MANOVA, $p < 0.05$) and post hoc tests with Bonferroni correction for pairwise comparisons. Sex and level group differences in $DBB_{displacement}$ were visualized as box-and-whisker plots and were assessed by a Kruskal-Wallis H-Test ($p < 0.05$) and a post hoc method with the Bonferroni correction. In U16 skiers, relationships between $DBB_{displacement}$ and the cofounding factors *age, maturity offset, body height, and body weight* were described using Pearson correlation ($p < 0.05$). The relationship between $DBB_{displacement}$ and *skiing performance* was assessed by Spearman's rank correlation ($p < 0.05$). Correlation coefficients were interpreted according to Cohen (1988): *large* (>0.5), *moderate* (0.5–0.3), *small* (0.3–0.1), *insubstantial* (<0.1). Finally, the association between $DBB_{displacement}$ and the occurrence of back overuse complaints was analysed by using binary logistic regression ($p < 0.05$).

3. Results

3.1. Test-retest reliability

On a group level, the repeated measures ANOVA revealed no significant differences in $DBB_{displacement}$ between the 5 repetitions at $p < 0.05$ (31.6 ± 5.5 mm, 33.1 ± 9.2 mm, 33.3 ± 7.5 mm, 35.3 ± 8.5 mm, 34.8 ± 9.2 mm). The test-retest reliability of the $DBB_{displacement}$ assessment was found to be *good* (ICC(3,1) and 95% CI of 0.81 [0.61, 0.93]). Within-subject SEM was 3.89 mm [3.16 mm, 5.12 mm] and standardized typical error revealed to be *moderate* (0.48 [0.39, 0.63]).

3.2. Baseline characteristics and biological maturation

An overview of athletes' baseline characteristics of the main experiment is presented in Table 1. The 12 healthy subjects of the reliability experiment had an average age of 28.6 ± 5.0 y, height of 172.4 ± 8.7 cm, weight of 68.1 ± 9.9 kg and BMI 22.8 ± 1.6 kg/m^2.

3.3. DBB performance in competitive alpine skiers

$DBB_{displacement}$ results in two distinct populations (i.e. U16 and elite skiers) and corresponding sex differences are illustrated in Fig. 2. At $p < 0.001$, there was a significant difference in the central tendency (median (Q_1 - Q_3)) of $DBB_{displacement}$ between female U16 (43 mm (37 mm–52 mm)) and female elite skiers (29 mm (25 mm–40 mm)) with a median difference of −14 mm, as well as between male U16 (45 mm (36 mm–53 mm)) and male elite skiers (29 mm (26 mm–34 mm)) with a median difference of −16 mm. However, between females and males of the same age and level group, no differences were observed (U16 skiers: $p = 0.980$; elite skiers: $p = 0.630$). The largest within group variation was found for female elite skiers, while for all other groups internal variation was of comparable magnitude.

3.4. Relationship between DBB performance, age, anthropometrics and biological maturation

In U16 skiers, there were no significant correlations $p < 0.05$ between $DBB_{displacement}$ and the cofounding factors *age* ($r = -0.121$, $p = 0.167$), *maturity offset* ($r = -0.039$, $p = 0.657$), *body height* ($r = -0.009$, $p = 0.918$), *body weight* ($r = -0.057$, $p = 0.514$), and BMI ($r = -0.074$, $p = 0.399$).

3.5. Relationship between DBB performance and skiing performance

On average, the group of U16 skiers had 83.5 ± 28.3 performance points according to the Swiss national ranking list (U16 female: 78.4 ± 23.2; U16 male: 86.5 ± 30.6). Between $DBB_{displacement}$ and the *skiing performance* of U16 skiers, i.e. the performance points according to the Swiss national ranking list, a *small* positive linear relationship (Spearman's rank correlation: $r = 0.214$, $p = 0.013$); see APPENDIX 1. The test measure $DBB_{displacement}$ was able to explain 4.6% of the variance in skiing performance observed ($R^2 = 0.046$).

3.6. Association between DBB performance and back overuse complaints

24.1% of the U16 skiers suffered from at least one back pain episode within the 12 months health observation (U16 female: 30.6%; U16 male: 20.2%). 10.5% of all U16 skiers even reported substantial back overuse complaints (U16 female: 16.3%; U16 male: 7.1%). A binary logistic regression analysis in U16 skiers revealed a significant direct association between the predictor $DBB_{displacement}$ and the dependent variable substantial back overuse complaints [yes; no] at $p < 0.05$, see Table 2. An increase of $DBB_{displacement}$ by one unit (i.e. 1 mm) increased the relative probability of suffering from substantial back overuse by 4.9% (odds ratio 1.049).

4. Discussion

Major findings were: (1) Test-retest reliability of the proposed biomechanical approach revealed to be *good* and the (standardized) within-subject SEM to be *moderate*; (2) The outcome measure $DBB_{displacement}$ significantly differed between U16 and elite skiers, whereas there were no sex differences between skiers of the same level group; (3) In U16 skiers, $DBB_{displacement}$ was not correlated with *age*, *maturity offset*, *body height*, or *body weight*. There was a small correlation between $DBB_{displacement}$ and *skiing performance* of U16 skiers. $DBB_{displacement}$ was found to be significantly associated with the occurrence of back overuse complaints in U16 skiers.

4.1. An objective, reliable and valid biomechanical assessment of DBB performance appears feasible

To date, there is no standardized methodology for the assessment of the athletes' rear-chain stabilization capacity. As for any

Table 1
Baseline characteristics.

	U16		Elite	
	Female (n = 49)	Male (n = 84)	Female (n = 19)	Male (n = 19)
age [y]	14.7 ± 0.6	14.9 ± 0.6	21.3 ± 2.8***	23.4 ± 2.6###,***
maturity offset [y]	2.1 ± 0.6	0.6 ± 0.8###	–	–
Body height [cm]	162.4 ± 5.9	167.4 ± 7.8###	166.2 ± 5.8	179.0 ± 7.1###,***
body weight [kg]	54.2 ± 7.2	56.5 ± 10.3	65.6 ± 5.9***	83.5 ± 8.6###,***
BMI [kg/m²]	20.5 ± 2.1	20.0 ± 2.3	23.7 ± 1.8***	26.0 ± 1.7###,***

All data are presented as mean ± SD. Level of significance based on a multivariate analysis of variance (MANOVA; $p < 0.001$, $eta_p^2 = 0.562$) and post hoc method with Bonferroni correction for pairwise comparisons: females vs. males of the same level group (### $p < 0.001$); U16 athletes vs. elite athletes of the same sex (*** $p < 0.001$). Pairwise comparisons were backed-up by bias corrected accelerated (BCa) bootstrapping with 10′000 samples. U16: skiers competing at the aged under 16 years category.

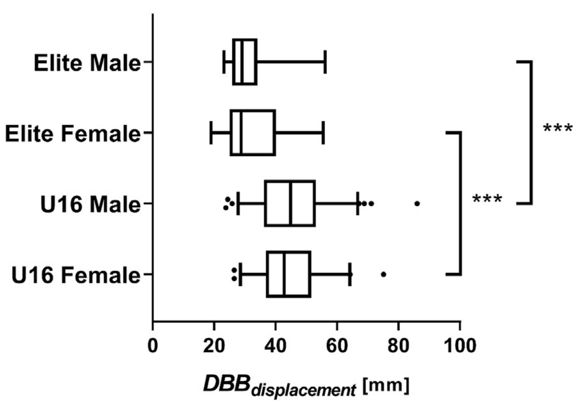


Fig. 2. Deadbug bridging performance ($DBB_{displacement}$) in male and female U16 and elite competitive alpine skiers. Data are expressed as median; boxes represent Q1-Q3 and Whiskers 5–95 percentile. Outlier are marked as single points. Level of significance based on the Kruskal-Wallis H-Test (Chi-Square = 41.883, $p < 0.001$) and post hoc method with Bonferroni correction for pairwise comparison: ***$p < 0.001$; U16: skiers aged under 16 years.

new physical performance test, first and foremost, our *DBB*-based approach's objectivity, test-retest reliability and (criterion, content-related and construct) validity needs to be critically assessed.

Regarding **objectivity**, an accurate quantitative assessment of athletes' stabilization performance is key; a demand that we addressed by incorporating an optoelectronic, marker-based 3D motion capture system. With respect to **reliability**, a potential quantitative assessment needs to be highly repeatable. In this regard, our reliability experiment revealed a *good* test-retest reliability. The within-subject SEM values were two to three orders of magnitude smaller than the variation in the different non-athletic and athletic subgroups assessed, which may be deemed acceptable. Moreover, $DBB_{displacement}$ has been shown to be independent of potential cofounding factors such as age, anthropometrics, and biological maturation; a fact that is of particular importance when testing youth athletes. Concerning **validity**, a reasonable assessment approach needs to fulfil further criteria: (1) *criterion validity*: providing certain sports practical and/or clinical relevance, as it was shown for our approach by the association of $DBB_{displacement}$ with both skiing performance and back overuse complaints; (2) *content-related validity*: addressing the sport-specific function of the tested stabilization capacity; a criterion that our *DBB* test meets in the broader sense. In alpine skiing, the sport-specific function of the athletes' rear-chain stabilization capacity is primarily related to adequate force transmission during cyclic changes of direction and ski-snow-interaction induced (mostly foreseeable) perturbations of the dynamic equilibrium (Reid et al., 2020). While the *DBB* test realistically imitates the dynamic trunk control under quasi-static conditions with focus on lateral bending and torsion of the trunk (two important components of mechanisms leading to back overuse injuries in alpine ski racing (Spörri et al., 2015)), our approach clearly differs in the knee, hip and trunk angles of the sagittal plane. However, in this regard content-related validity might be inversely related with test-retest reliability, and we decided to prioritise the standardisation advantages of the closed-chain *DBB* test in contrast to any stability task with an open kinematic chain in standing/tucked skiing positions. (3) *construct validity*: following the construct of the anatomical structures required for stabilization being a global system and single muscles not being trainable separately (Wirth et al., 2017), also testing should be done globally. In this connection, our *DBB*-based approach for quantifying athletes' rear-chain stabilization capacity especially accounts for the characteristic movement and loading patterns in competitive alpine skiing. These do not only require high stabilization capacities of the paraspinal muscles, but also those of the entire rear chain (including the posterior trunk, pelvic gridle and leg muscles). Conversely, *DBB* could be specifically used as a training exercise. In conclusion, an objective, reliable and valid biomechanical assessment of *DBB* performance in competitive alpine skiers appears feasible. Moreover, the proposed approach may also open up new perspectives for assessing core stability in other contexts, such as different sports or clinical settings.

4.2. Towards alpine skiing-specific reference values

This study provided first reference values for the assessment of competitive alpine skiers. Depending on sex and sportive level, median $DBB_{displacement}$ magnitudes ranged between 29 mm and 45 mm. To what extend these values are representative for other athletic cohorts or non-athletic subjects remains to be investigated.

Interestingly, the largest within group variation was found for female elite skiers, while for all other groups the internal variation was of comparable magnitude. Based on the data of the current study the origin of this finding remains unclear. However, from a

Table 2
Binary logistic regression analysis assessing the association of deadbug bridging performance ($DBB_{displacement}$) with the occurrence of substantial back overuse complaints of the back in athletes around the growth spurt, i.e. U16 skiers.

Model Parameter (n = 133)	Dependent Variable	Independent Variable	B	e^B	SE_B	P-value[a]
Chi-Square = 3.875, p = 0.049, $R^2_{Nagelkerke}$ = 0.059, Cohen f = 0.25	substantial back overuse complaints [yes; no]	$DBB_{displacement}$ [mm]	0.047*	1.049	0.024	0.048*

[a] Level of significance: * $p < 0.05$.

purely speculative point of view, the substantially larger $DBB_{displacement}$ variation in female elite skiers might be explained by more frequent athletic deficits in females than among males when entering the elite level. At least, such line of argumentation coincides with the previously reported expert stakeholders' perception that younger athletes, in particular women, are not always sufficiently prepared to enter the World Cup level (Spörri, Kröll, Amesberger, Blake, & Müller, 2012).

Another important finding is the fact that $DBB_{displacement}$ significantly differed between U16 and elite skiers, whereas there were no sex differences between skiers of the same level group. Thus, in contrast to trunk muscle strength, where clear differences between female and male athletes have been reported (Arampatzis, Frank, Laube, & Mersmann, 2019; Mueller, Mueller, Stoll, Baur, & Mayer, 2014), the stabilization performance during *DBB* appears to be independent of sex. However, despite this discrepancy in terms of sex differences and in the knowledge that trunk strength and stabilization represent two fundamentally different concepts, both aspects should be tested in skiers in a complementary manner. In particular, because in this and a previous study (Raschner et al., 2012), both were found to be associated with the risk of injury.

4.3. Superior deadbug bridging performance – a performance-relevant factor in skiers?

Within coaching communities, it is commonly believed that a superior postural stability plays an important role for good performance, while there is in fact a lack of research investigating the effect of postural stability on sporting performance (Hibbs et al., 2008). This hypothesis may be primarily argued by an increase in movement precision and consistency when athletes are able to keep their body in a dynamic equilibrium. In a similar manner, the ability to maintain a stable position on the skis while being exposed to external perturbations may help avoiding mistakes and increasing performance. Certainly, skiing performance is multifactorial and complex (Hebert-Losier, Supej, & Holmberg, 2014), and given the small correlation observed, our *DBB*-based stability test does not claim to be the method of choice for performance prediction or talent selection purposes. Nevertheless, there is a certain association between *DBB* performance and skiing performance, which is why the training and testing of the rear chain stabilization capacities in skiers highly recommendable. Not least because of the fact that $DBB_{displacement}$ (i.e. a single off-snow test measure) is able to explain 4.6% of the variance in skiing performance (i.e. a dependent variable wide range of influencing factors).

4.4. Poor deadbug bridging performance – a back overuse injury relevant factor in skiers?

As stated above, the demands on competitive alpine skiers' physical fitness are high (Gilgien et al., 2018; Kröll et al., 2015). Especially, adequate force transmission and superior stabilization capacities are required in order to bear the adverse loading patterns of the spine while skiing (Spörri et al., 2015). Indeed, our analysis revealed $DBB_{displacement}$ of U16 skiers to be significantly associated with back overuse complaints. An increase of $DBB_{displacement}$ by one unit (i.e. 1 mm) increased the relative probability of suffering from substantial back overuse by 4.9%. Again, in view of the multifactorial nature of developing back pain, this is a remarkable magnitude for a single factor of a complex system, further highlighting the relevance of training and testing the rear chain stabilization capacities in skiers. On the basis of the data from this cross-sectional study, however, it remains to be questioned (and to be answered) whether poor deadbug bridging performance can be considered a significant injury risk factor for back overuse complaints and/or whether *DBB*-based tests could be used for screening purposes.

4.5. Methodological considerations

There are two study limitations one should be aware of: First, this study quantified *DBB* performance as a single kinematic measure, $DBB_{displacement}$, whereas the underlying neuromuscular mechanisms remain unclear. In this connection, electromyography and imaging-based approaches may contribute to a better understanding of the operating principles of core muscles to ensure stability. Second, due to the study's cross-sectional design, only the aspect of concurrent validity (e.g. the correlation between *DBB* performance and actual skiing performance/back overuse complaints) was assessable. The predictive validity of *DBB* performance, however, remained unexplored and could be the subject to further longitudinal studies.

5. Conclusion

This study introduced a novel biomechanical approach to quantify athletes' stabilization performance during *DBB* and provided data on test-retest reliability and reference values across sexes and different levels of competitive alpine skiers. As $DBB_{displacement}$ revealed to be independent of age, anthropometrics, and biological maturation, however, was directly associated with skiing performance and back overuse complaints in U16 skiers, our approach may serve as a valuable tool to quantify athletes' rear-chain stabilization capacity during *DBB*.

Funding

This study was generously supported by the Balgrist Foundation, Swiss-Ski, the "Stiftung Passion Schneesport", and the "Stiftung zur Förderung des alpinen Skisportes in der Schweiz (SFSS)".

Public involvement

The aim of involving athletes and expert stakeholders in the current study was (1) to orientate our research on the actual sports-practical and clinical demands of competitive sports communities, (2) to achieve a maximal athlete and stakeholder adherence, and (3) to ensure a successful knowledge translation into the real-world settings of youth and elite athlete development structures. Accordingly, expert stakeholders (e.g. coaches and medical staff) were involved in developing the study design. During the conduct of the study, athletes and their direct personal environment (e.g. parents) were informed and empowered for maintaining a superior adherence to study tasks, such as the two-weekly reporting of occurring health problems. Personal study results were disseminated to the athletes and their direct personal environment by email and were, upon request, interpreted in collaboration with their coaches. Finally, the overall major results were communicated within the National Ski Federation Swiss-Ski as well as related regional youth development structures, and will find direct application in the national training and screening concept of Swiss-Ski in the near future.

Ethical statement

Participants of both experiments provided written consent after receiving detailed information about the study. An institutional review committee and local ethics committee (KEK-ZH-NR: 2017–01395) approved the study that is in conformity with the Helsinki Declaration and national laws.

Authors contribution

JS conceptualised and designed the study. JS recruited the participants and organised the data collection. LE, JJ, SF and JS collected the data. LE, JJ, SF and JS processed the data and performed the statistical analysis. All authors contributed to the interpretation of data. LE and JS drafted the current manuscript; all authors revised it critically, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

Declaration of competing interest

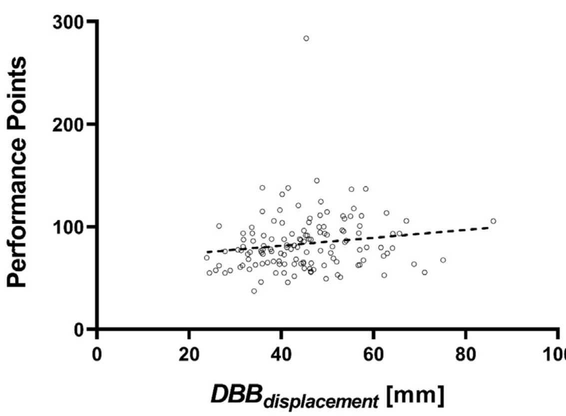
No conflict of interest declared.

Acknowledgments

We would also like to thank all participants, parents, and coaches involved.

Appendix 1

Relationship between Deadbug bridging performance ($DBB_{displacement}$) and the skiing performance of U16 skiers, i.e. the performance points according to the Swiss national ranking list.



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