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SYSTEMATIC REVIEW

The Epidemiology of Injuries Across the Weight-Training Sports

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Abstract

Background Weight-training sports, including weightlifting, powerlifting, bodybuilding, strongman, Highland Games, and CrossFit, are weight-training sports that have separate divisions for males and females of a variety of ages, competitive standards, and bodyweight classes. These sports may be considered dangerous because of the heavy loads commonly used in training and competition.

Objectives Our objective was to systematically review the injury epidemiology of these weight-training sports, and, where possible, gain some insight into whether this may be affected by age, sex, competitive standard, and bodyweight class.

Methods We performed an electronic search using PubMed, SPORTDiscus, CINAHL, and Embase for injury epidemiology studies involving competitive athletes in these weight-training sports. Eligible studies included peer-reviewed journal articles only, with no limit placed on date or language of publication. We assessed the risk of bias in all studies using an adaption of the musculoskeletal injury review method.

Results Only five of the 20 eligible studies had a risk of bias score ≥75 %, meaning the risk of bias in these five studies was considered low. While 14 of the studies had sample sizes >100 participants, only four studies utilized a prospective design. Bodybuilding had the lowest injury rates (0.12–0.7 injuries per lifter per year; 0.24–1 injury per 1000 h), with strongman (4.5–6.1 injuries per 1000 h) and Highland Games (7.5 injuries per 1000 h) reporting the highest rates. The shoulder, lower back, knee, elbow, and wrist/hand were generally the most commonly injured anatomical locations; strains, tendinitis, and sprains were the most common injury type. Very few significant differences in any of the injury outcomes were observed as a function of age, sex, competitive standard, or bodyweight class.

Conclusion While the majority of the research we reviewed utilized retrospective designs, the weight-training sports appear to have relatively low rates of injury compared with common team sports. Future weight-training sport injury epidemiology research needs to be improved, particularly in terms of the use of prospective designs, diagnosis of injury, and changes in risk exposure.

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Key Points

The weight-training sports appear to have lower rates of injury than many common team sports. However, it is acknowledged that this conclusion may partly reflect some limitations in the weight-training sport injury epidemiology literature, primarily study design, diagnosis of injury, and changes in risk exposure.

Each of the weight-training sports tended to have some subtle differences in their injury epidemiology, particularly their proportional injury rates across the various anatomical locations as well as the onset and severity of injury.

The intrinsic factors of sex, competitive standard, age, and bodyweight class may only have a relatively minor influence on the injury epidemiology of the weight-training sports.

1 Introduction

Weight training is a popular physical activity typically performed to increase muscular hypertrophy, strength, and endurance. Weight training typically uses the force of gravity acting upon resistances, including the exerciser's own bodyweight or specialized forms of equipment such as barbells, dumbbells, and resistance-training machines to target specific muscle groups and joint actions. While many people who regularly exercise perform weight-training along with cardiovascular or flexibility exercise for overall health benefit, several athletic groups also compete in sports in which weight training is the primary form of training and/or the competitive event. These sports include weightlifting, powerlifting, bodybuilding, strongman, Highland Games, and CrossFit.

Weightlifting requires the lifter to lift maximal loads for one repetition in two exercises: the clean and jerk and the snatch. As these exercises require the barbell to be lifted explosively from the floor to an overhead position, they may produce the greatest power outputs of any human activity [1]. Up until 1972, weightlifting also involved a third lift, the overhead (shoulder) press. Powerlifting is similar to weightlifting, with lifters attempting to lift the maximum loads for one repetition. However, in powerlifting competitions, the three lifts performed are the squat, bench press, and deadlift.

The Scottish Highland Games and strongman competitions are in some ways the most similar form of weight-training competition to that performed in ancient or medieval times, with some of the events found in the sports traditionally performed as tests of manhood in many countries. These tests of manhood typically had farming and/or military applications and involved the lifting or throwing of a variety of natural and man-made objects that have been available for hundreds or thousands of years. Specifically, strongman events utilize a variety of heavy implements such as stones for lifts and carries, tires for flipping, logs and stones for overhead pressing, and trucks or sleds for pulling. While some of these strongman events are similar to weightlifting and powerlifting, with the athletes attempting to lift the heaviest load for one repetition, many of the events are timed, with the winner being the fastest athlete to complete the task. Highland Games events are further ancient/mediaeval examples of tests of manhood and typically involve a range of heavy throwing events such as the caber, stone put, hammer throw, or sheaf toss, as well as weight for height and distance. The variety of weight-for-distance events are simply much heavier versions of many of the throwing events currently seen in regular track and field competitions.

CrossFit is the newest of the weight-training sports. CrossFit programs, known as 'workouts of the day' (WODs), typically exceed 10–20 min and include a variety of bodyweight and resistance exercises, gymnastics, weightlifting, powerlifting, and endurance activities. These exercises are generally combined into high-intensity workouts performed in rapid succession with limited or no recovery time. CrossFit athletes also compete in the CrossFit games, where the winner is the athlete who completes the WOD in the shortest period of time.

Bodybuilding differs from the other weight-training sports in that it is not judged on the weight lifted or the time taken to complete an event, but rather on the physical appearance of the athlete. Bodybuilding competitors therefore also perform regular high-intensity weight training to develop muscle bulk, balance between muscle groups (symmetry), muscular density, and definition, as these criteria are judged in competition.

Most of these weight-training sports included in this review have annual world championship events for male and female athletes, with some of these sports also offering various bodyweight or age (junior, open, and masters) classes. However, weightlifting is the only one of these sports currently included in the Olympic Games, although powerlifting (bench press only) is also a part of the Paralympics. Figure 1 shows some common weight-training exercises performed by the athletes competing in the sports.

Given the intense, heavily loaded activities commonly performed by these athletes in training and competition, the joint moments (torques) as well as shear and compressive

Fig. 1 Illustration of various events/poses in the weight training sports: **a** weightlifting (Carl Pilon), **b** powerlifting (Mitya Galiano), **c** bodybuilding (Amanda Richards), **d** CrossFit (CrossFit Auckland), **e** strongman (Shaun Ellis), and **f** Highland Games (Alain Cadu). Photos reprinted with permission from respective photographers (acknowledged in *brackets*)

forces produced during these types of exercises can be very large [1–5]. Members of the public, sporting, medical, and scientific communities may therefore believe these activities are inherently dangerous and that their performance will result in numerous serious and/or long-term injuries. Such a view may also reflect the many case studies found in the literature in which needless weight training-related severe injuries [6, 7] and catastrophic incidents have been reported [8, 9]. According to the National Center for Catastrophic Sport Injury Research [10], catastrophic injuries can be defined as "fatalities, permanent disability injuries, serious injuries (fractured neck or serious head injury) even though the athlete has a full recovery, temporary or transient paralysis (athlete has no movement for a short time, but has a complete recovery), heat stroke due to exercise, or sudden cardiac arrest or sudden cardiac or severe cardiac disruption." While these case studies highlighting the risks of weight training are important to acknowledge, the primary objective of this analysis was to systematically review the injury epidemiology of these weight-training sports using a list of injury epidemiology outcomes advocated by the International Olympic Committee (IOC) [11]. The secondary objective was to gain some insight into whether demographic characteristics such as age, sex, competitive standard, and bodyweight class influenced the injury epidemiology of these weight-training sports.

2 Methods

2.1 Search Strategy and Inclusion Criteria

No review protocol for this paper currently exists, although this manuscript is an update of a previous literature review published as a chapter in a 2009 IOC text on sporting injury [12]. The original book chapter included ten journal articles (all of which are cited in the current review) as well as two abstracts. Neither of these abstracts were deemed eligible for this current review, as neither contained sufficient detail to determine their risk of bias (ROB). As a result of the increased research into weight-training injury and the emergence of CrossFit and—to a lesser extent—strongman as new participation sports since the previous book chapter, the authors believe such an update has considerable merit.

We conducted a search using PubMed, CINAHL, SPORTDiscus, and Embase up to 15 September 2015. As the focus was on quantifying the injury epidemiology of the weight-training sports, we adopted a three-level approach. The first level involved using derivatives of the terms injury, weightlifting, powerlifting, bodybuilding, strongman, Highland Games, and CrossFit so as to identify injury studies involving these sports. The second level meant that the studies had to utilize an injury epidemiology rather than case study design. The third level required the studies to contain key words relating to injury, including wound, rupture, sprain, strain, and tear. The full search strategy for the PubMed search was ((injur*[Text Word] OR rupture*[Text Word] OR sprain*[Text Word] OR strain*[Text Word] OR tear*[Text Word]) OR "Wounds and Injuries"[Medical Subject Heading; Mesh]) AND ("Weight Lifting"[Mesh] OR weight lift*[Text Word] OR weightlift*[Text Word] OR power lift*[Text Word] OR powerlift*[Text Word] OR body build*[Text Word] OR bodybuild*[Text Word] OR strongman[Text Word] OR "strong man"[Text Word] OR "Highland Game"[Text Word] OR "Highland Games"[Text Word] OR "Cross fit"[Text Word] OR CrossFit[Text Word])) AND (injur* AND weight lift* OR weightlift* OR power lift* OR powerlift* OR body build* OR bodybuild* OR strongman OR strong man OR Highland Game OR Crossfit OR CrossFit).

To be included in this review, the studies had to be full articles published in peer-reviewed journals and contain a description of the injury epidemiology of at least one of the weight-training sports. Articles in any language were accepted; this resulted in the inclusion of 15 articles written in English, two in Chinese, two in German, and one in Korean. As neither of the two authors were able to read Chinese, German, or Korean, the authors sought the assistance of one Chinese colleague, one German colleague, and Google Translate to assist in the translation of these articles, respectively. The two authors provided their Chinese and German colleagues with sufficient assistance to quantify the risk of bias and to extract the relevant information for the systematic review, as performed by the two authors on the remaining 16 papers.

No restrictions were placed on the year of publication, and no effort was made to contact any of the study authors to identify additional studies. All of these studies involved adults, except that of Brown and Kimball [13], who examined the retrospective injury epidemiology of 71 adolescent powerlifters aged 14–19 years. For those interested in a more in-depth discussion on the injury risk of weight training for children, the reader should consult Malina [14], Faigenbaum et al. [15], or Lloyd et al. [16].

Two independent reviewers (JK and PW) removed duplicate studies then screened all study titles. The same reviewers (authors) retrieved the full text of all potentially eligible articles and evaluated them for eligibility. They also scanned the reference lists of these articles for other potentially relevant articles that were not initially identified in the database searches. All included article titles were then tracked forward by citation tracking using Google Scholar to find any other potentially relevant articles that could be included in the review. Any disagreements between the two authors regarding the inclusion of studies within this review were resolved in a consensus meeting.

2.2 Risk-of-Bias Assessment and Data Extraction

Both authors and, where relevant, the Chinese and German colleagues independently assessed the ROB of the eligible studies using a checklist (Electronic Supplementary Material [ESM] Table S1) developed for assessing the ROB in studies examining musculoskeletal injury [17–19]. Any disagreements between the two authors regarding the ROB of the eligible studies were resolved in a consensus meeting. Table 1 shows the results of the bias assessment. All items were scored as positive (+) or negative (−) for studies with a low or high ROB, respectively. The item was scored as negative if no clear information was given regarding the item or if it was unclear whether the ROB criteria for an item was met. The total ROB score for each study was calculated by counting the number of items that were scored positively, expressed as a percentage of all items. Articles with a ROB score ≥75 % were considered as having a low ROB [19].

2.3 Data Analysis

Consistent with the IOC recommendations [11], the data from the included epidemiology studies were categorized into the following primary sections: who is affected by injury, where does injury occur, when does injury occur, what is the outcome, what are the risk factors, and what are the inciting events? Where data were reported for specific demographic groups based on age, sex, competitive standard, or bodyweight class, results for these additional subgroup analyses were also reported. The primary variable of interest was injury rates, which were reported in two ways: (1) injury per athlete per year and/or (2) injury per 1000 h of exposure, where possible. We provide a discussion of the results within each of the result sections as we felt it made for an easier integration of the large level of data presented and their potential interpretations, applications, and limitations.

Table 1 Risk of bias assessment of the studies

Study	Risk of bias assessment of the studies											
	1	2	3	4	5	6	7	8	9	10	11	Overall risk of bias rating (%)
Weightlifting												
Calhoon and Fry [27]	+	+	+	−	+	+	+	+	+	−	+	82
Engebretsen et al. [22]	+	+	+	+	+	+	−	+	+	+	−	82
Junge et al. [28]	+	+	+	+	+	+	−	+	+	+	−	82
Kim and Kim [24]	+	+	+	−	+	+	+	+	+	+	+	91
Konig and Biener [36]	−	−	−	+	−	+	−	+	−	−	−	27
Kulund et al. [35]	−	−	−	−	−	+	−	+	−	−	−	18
Raske and Norlin [25][a]	+	−	+	+	−	+	+	+	−	−	+	64
Wang et al. [23]	−	−	+	+	+	+	−	+	−	+	−	55
Powerlifting												
Brown and Kimball [13]	+	−	+	−	+	+	−	+	23 %[b]	−	−	47
Goertzen et al. [21][c]	−	−	+	+	−	+	−	+	23 %[b]	−	−	38
Haykowsky et al. [29]	+	−	+	−	+	+	+	+	+	−	+	73
Keogh et al. [20]	+	−	+	+	−	+	+	−	57 %[b]	−	+	60
Siewe et al. [30]	+	−	+	+	−	+	−	+	−	−	+	55
Bodybuilding												
Eberhardt et al. [38]	−	−	+	+	−	+	−	+	−	−	+	45
Siewe et al. [31]	+	−	+	−	−	+	−	+	39 %[b]	−	+	49
Xiaojun and Taotao [37]	−	−	+	+	+	+	−	+	−	+	−	55
Strongman												
Winwood et al. [26]	+	−	+	+	−	+	+	+	41 %[b]	+	+	76
Highland Games												
McLennan and McLennan [32]	+	−	+	+	−	−	−	+	−	−	+	45
CrossFit												
Hak et al. [33]	+	−	−	+	−	+	−	+	−	−	+	45
Weisenthal et al. [34]	+	−	+	+	−	+	+	+	−	−	−	55
Number of 20 studies with "Yes" response	14	4	17	14	8	19	7	19	6.8	6	11	

Method for assessing risk of bias: (1) Definition of injury clearly described; (2) prospective design used; (3) clear description of subject demographics within the study; (4) subject sample size ≥100; (5) inclusion process of participants was at random or the data collection was performed with the entire target population; (6) data analysis conducted in at least 80 % of the included subjects; (7) data collection appropriate—for prospective studies, at least a 6-month follow-up, for retrospective studies up to a 12-month recall period; (8) same mode of data collection (e-mail, telephone, interview, etc.) used; (9) injury diagnosis conducted by health professionals; (10) changes in risk exposure taken into account (i.e., seasonal changes, periodized block, training vs. competition); (11) number of injuries reported by exposure time to weight training. Note: If there was insufficient information in the article to permit a judgment for a particular criterion, the answer was "No: high risk of bias" for that particular criterion. % indicates the percentage of injuries diagnosed by a medical professional; + indicates yes: low risk of bias; − indicates no: high risk of bias

[a] Study includes powerlifting and weightlifting athletes

[b] Percentage of subjects who reported the injury was medically diagnosed

[c] Study includes powerlifting and bodybuilding athletes

3 Results and Discussion

3.1 Literature Search

An examination of 4021 titles (including 411 duplicates) revealed 184 potentially relevant full-text articles, which were retrieved. After review of the full text, a further 167 articles were excluded. The 17 eligible studies were then reviewed, with their reference lists also checked to identify other potentially eligible studies that may have been missed in the initial search. This process revealed another two eligible studies, resulting in a total of 19 studies. The 19 studies were then forward tracked in time by citation tracking using Google Scholar, which found one more study, resulting in a total of 20 studies in this review. Figure 2 presents a pictorial representation of the literature search.

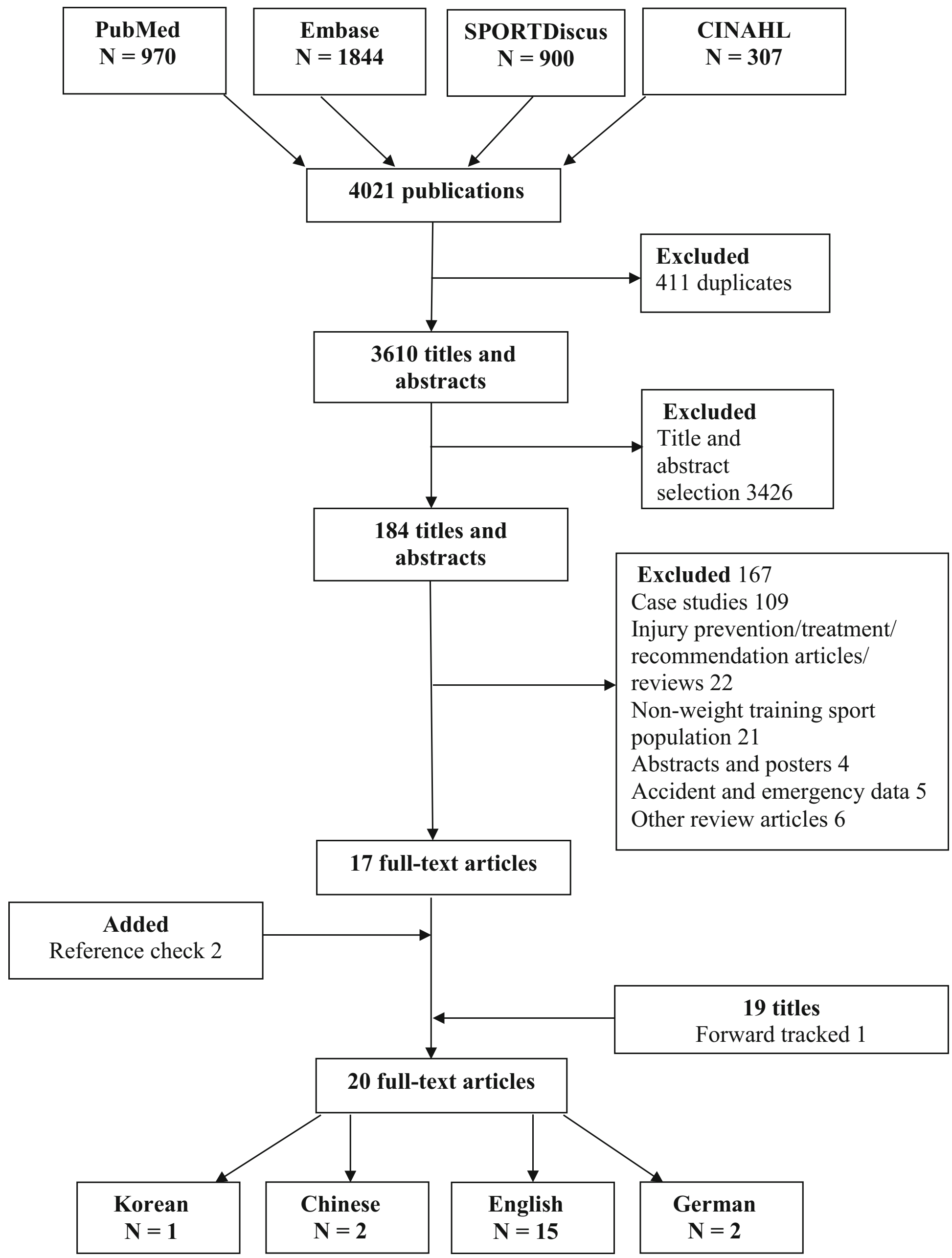

Fig. 2 Flow chart of the article selection process

Within the 20 eligible studies, data were presented for weightlifting (eight studies) and powerlifting (six studies). We also identified four studies for bodybuilding, one study of strongman, one study of Highland Games, and two studies for CrossFit injury epidemiology. There was often considerable intra- and/or inter-study variation in the age, sex, body mass, and standard of the lifters, with a small number of the studies reporting data for these sub-groups. Specifically, several studies categorized (at least some of) their data by sex [20–24], competitive standard [20, 23, 25, 26], age [20, 26], and bodyweight class [20, 26].

3.2 Risk of Bias

Table 1 displays the results of the ROB assessment. Five of the 20 studies had a score ≥75 % and were considered to have a low ROB [19]. The definition of injury was clearly described in 14 studies [13, 20, 22, 24–34], with these definitions typically requiring an injury to involve physical damage to the athlete that caused the athlete to modify or cancel at least one training session. Table 2 provides a summary of the definitions provided in these papers. Four of the included studies used a prospective design [22, 24, 27, 28]. Three studies did not clearly describe the

Table 2 Summary of studies injury/pain definition

Study	Injury/pain definition
Weightlifting	
Calhoon and Fry [27]	Injuries were defined by classifications: Acute injuries are "injuries with rapid onset due to traumatic episode, but with short duration." A chronic injury is "an injury with long onset and duration." A recurring injury involves recovery and re-injury for a particular condition"
Engebretsen et al. [22]	Injury was defined as a "new or recurring musculoskeletal complaints or concussions or illnesses incurred during competition or training during the London Olympic Games (27 July–12 August 2012) receiving medical attention, regardless of the consequences with respect to absence from competition or training"
Junge et al. [28]	An injury was defined as "any musculoskeletal complaint (traumatic and overuse) newly incurred due to competition and/or training during the XXIX Olympiad in Beijing that received medical attention regardless of the consequences with respect to absence from competition or training"
Kim and Kim [24]	An injury was defined as "any musculoskeletal symptoms and signs that required medical attention"
Konig and Biener [36]	No formal definition of injury provided
Kulund et al. [35]	No formal definition of injury provided
Wang et al. [23]	No formal definition of injury provided
Powerlifting	
Brown and Kimball [13]	Subjects responded to questionnaire items on types and sites of injuries that were severe enough to cause them to discontinue training for at least 1 day
Goertzen et al. [21][a]	No formal definition of injury provided
Haykowsky et al. [29]	Injury was defined as "the number and severity of powerlifting-related injuries that required medical intervention (from a physician, chiropractor, or physical therapist) and that resulted in an interruption in training for more than one day within the last year was assessed"
Keogh et al. [20]	Injury was defined as "any physical damage to the body that caused the lifter to miss or modify one or more training sessions or miss a competition"
Raske and Norlin [25][b]	The definition of injury was "an inability to train or compete as planned"
Siewe et al. [30]	Injury was defined as "an incident leading to an interruption in training or competition"
Bodybuilding	
Eberhardt et al. [38]	No formal definition of injury provided
Siewe et al. [31]	Injury was defined as "an incident provoking an interruption in either training or competition"
Xiaojun and Taotao [37]	No formal definition of injury provided
Strongman	
Winwood et al. [26]	Injury was defined as "any physical damage to the body that caused the strongman athlete to miss or modify one or more training sessions or miss a competition"
Highland Games	
McLennan and McLennan [32]	Injury was defined as "a mishap occurring during meets or training that resulted in the inability to compete or practice normally"
Crossfit	
Hak et al. [33]	Injury was defined as "any injury sustained during training which prevented the participant training, working or competing in any way and for any period of time"
Weisenthal et al. [34]	Injury encompassed any new musculoskeletal pain, feeling, or injury that results from a CrossFit workout and leads to one or more of the following options: (1) total removal from CrossFit training and other outside routine physical activities for >1 week; (2) modification of normal training activities in duration, intensity, or mode for >2 weeks; and (3) any physical complaint severe enough to warrant a visit to a health professional

[a] Study includes powerlifting and bodybuilding athletes

[b] Study includes powerlifting and weightlifting athletes

participants' competitive level and/or demographic characteristics [33, 35, 36]. Fourteen studies used subject sample sizes ≥100 [20–23, 25, 26, 28, 30, 32–34, 36–38]. The criteria for the inclusion of participants (i.e., random, or data collection was performed with the entire target population) was clear in eight studies [13, 22–24, 27–29, 37]. In only one of the 20 studies did data analysis not represent at least 80 % of the included participants [32]. Seven studies employed an appropriate duration of data collection (i.e., for prospective studies, at least a 6-month follow-up; for retrospective studies, up to a 12-month recall period) [20, 24–27, 29, 34]. One study used different modes of data collection (e-mail, telephone, interview, etc.) [20]. A diagnosis of all injuries was conducted by health professionals in five studies [22, 24, 27–29] and partially in another five studies [13, 20, 21, 26, 31]. Six studies accounted for changes in risk exposure (e.g., seasonal changes, training vs. competition) [22–24, 26, 28, 37], and 11 studies reported number of injuries by exposure time to weight training [20, 24–27, 29–33, 38].

3.3 Who is Affected by Injury?

Injury incidence rates reported in Table 3 were somewhat consistent, with most studies reporting ~1–2 injuries per lifter per year or ~2–4 injuries per 1000 h. However, there were some exceptions to this rule. Studies reporting lower injury rates included three bodybuilding studies (0.12–0.7 injuries per lifter per year or 0.24–1 injury per 1000 h) [21, 31, 38] and two of the six powerlifting studies (0.3–0.4 injuries per lifter per year and 1.0–1.1 injuries per 1000 h) [29, 30]. Studies reporting higher injury rates included the only studies on strongman (2.0 injuries per lifter per year and 5.5 injuries per 1000 h of training) [26] and Highland Games (7.5 injuries per 1000 h of training and competition) [32].

The manner in which the injury incidence rate data were presented for the weightlifting study of Kim and Kim [24] precluded direct comparison with the other studies. While Kim and Kim [24] reported injuries per 1000 athlete exposures, they neither normalized their data to the number of weightlifters nor provided the number of weightlifters included in the study. Therefore, we were unable to determine the number of injuries per lifter per year or the number of injuries per 1000 h, as presented in previous studies.

As only one study was found for strongman and Highland Games, it is difficult to be certain that these sports have a greater injury risk than other weight-training sports. However, Winwood et al. [26] did quantify injury rates associated with different types of strongman training, reporting that, although only 31 % of strongman training involves specific implement (event) training, implement training accounted for 1.9 times more injury than traditional training (e.g., squat, deadlift, bench press) when normalized by time of exposure. Such results may indicate that strongman exercises by the nature of their dynamic movements may involve somewhat higher injury risk than traditional weight-training exercises performed with barbells, dumbbells, or weight-training machines.

A number of the studies also reported the athlete injury rate (i.e., the proportion of athletes who had suffered an injury [22, 23, 28, 30, 31, 34], with this varying from 16 to 90 %. Drawing comparisons between these studies is difficult as the time frame of data collection differed. At one extreme, Junge et al. [28] and Engebretzen et al. [22] collected data during Olympic competitions (16 and 17 days, respectively), whereas other studies [30, 31] collected data over the athletes' entire career. In contrast, Wang et al. [23] provided no specific timeframe for the duration of the data collection.

3.4 Where Does Injury Occur?

3.4.1 Anatomical Location

Inspection of the individual studies revealed that the five most commonly injured sites were typically the shoulder, lower back, knee, elbow, and wrist/hand across the weight-training sports (see Table 4). Almost all of these data were reported as percentage of overall injuries, with Raske and Norlin [25] and Kim and Kim [24] the only studies to also report incidence rates for each anatomical location. The finding that shoulder injuries accounted for a high percentage of all weight-training sports injuries in the studies (6–36 %) may reflect the frequent use of heavy loads and exercises such as the bench press and overhead presses (e.g., strict press, push press, or jerk) by these athletes. Kolber et al. [39] suggested the susceptibility of the shoulder complex to weight-training injury is partly due to the high compressive loads these exercises apply to a traditionally non-weight-bearing joint. Furthermore, the bench and overhead presses may place the shoulder in somewhat unfavorable positions, such as end-range external rotation while under heavy loads, predisposing the shoulder to both acute and chronic injuries [39, 40].

There were some subtle between-sport differences in the most common sites of injury. In descending order, the three most frequent injury sites appeared to be weightlifting (knee, lower back, and shoulder), powerlifting (shoulder, lower back, and knee), bodybuilding (shoulder, knee, and lower back), strongman (lower back, shoulder, and bicep), Highland Games (shoulder, knee, and lower back), and CrossFit (shoulder, lower back, and knee). However, it must be acknowledged that there was some between-study variation in the anatomical location categories and/or definitions utilized in these studies. Further, as anatomical location of injury was only examined in two CrossFit studies, one strongman study, and one Highland Games study, further research is required to better characterize the most commonly injured anatomical locations in these sports.

The subtle differences in the most commonly injured anatomical locations for these weight-training sports begs the question, what aspects of these sports may alter the most commonly injured body parts (anatomical locations), particularly as athletes in all of these weight-training sports often perform similar exercises, including squats, power cleans, deadlifts, and/or overhead presses. One answer may lie in the different competitive goals and training practices

Table 3 Summary of the incidence and frequency of weight training injuries

Study	Athletes	Study design	Study duration	Injuries (*n*)	Clinical incidence (injuries/lifter/years)	Injury incidence/rate (injuries/1000 h)	Sport injuries/1000 athlete exposures (1000 AEs)	Athlete rate (% injured)
Weightlifting								
Calhoon and Fry [27]	Open elite (NS)	Prospective	72 months	560		3.3[a]		
Engebretsen et al. [22]	149 M, 103 F open elite	Prospective	17 days[b]	44				18[c]
Engebretsen et al. [22]	149 M open elite	Prospective	17 days[b]	27				18[c]
Engebretsen et al. [22]	103 F open elite	Prospective	17 days[b]	16				16[c]
Junge et al. [28]	255 elite M and F	Prospective	16 days[b]	43				17[c]
Kim and Kim [24]	National M (NS)	Prospective	271 days	125			100 and 362[d]	
Kim and Kim [24]	National F (NS)	Prospective	271 days	82			129 and 173[d]	
Konig and Biener [36]	121 M	Retro quest	EC	202	1.7[e]			
Kulund et al. [35]	80 M	Retro quest	NS	111	1.4[e]			
Raske and Norlin [25][f]	50 open elite M	Retro quest	24 months	108	1.1	2.4		
Raske and Norlin [25][g]	50 open non-elite M	Retro quest	24 months	98	1.0	2.9		
Wang et al. [23]	195 open M	Retro quest	NS	NS				74
Wang et al. [23]	70 open F	Retro quest	NS	NS				90
Powerlifting								
Brown and Kimball [13]	71 junior novice M	Retro quest	17 months	98	1.0	2.8		
Goertzen et al. [21]	39 open M	Retro quest and orthopedic exam	18 months	120	2.1			
Goertzen et al. [21]	21 open F	Retro quest and orthopedic exam	18 months	40	1.3			
Haykowsky et al. [29]	9 M, 2 F open elite blind	Retro quest	12 months	4	0.4	1.1		
Keogh et al. [20]	82 M, 19 F	Retro quest	12 months	118	1.2	4.4		
Keogh et al. [20]	82 M	Retro quest	12 months	98	1.2	4.7		
Keogh et al. [20]	19 F	Retro quest	12 months	20	1.1	3.1		
Keogh et al. [20]	36 national	Retro quest	12 months	50	1.4	5.8		
Keogh et al. [20]	65 international	Retro quest	12 months	68	1.0	3.6		
Keogh et al. [20]	59 lightweight	Retro quest	12 months	62	1.1	4.3		
Keogh et al. [20]	42 heavyweight	Retro quest	12 months	56	1.3	4.4		
Keogh et al. [20]	59 open	Retro quest	12 months	62	1.1	4.0		
Keogh et al. [20]	42 masters	Retro quest	12 months	56	1.3	4.7		
Raske and Norlin [25][f]	50 open elite M	Retro quest	24 months	114	1.1	2.7		
Siewe et al. [30]	219 M, 26 F open, elite	Retro quest	EC	NS	0.3	1.0		43
Bodybuilding								
Eberhardt et al. [38]	250 open M	Retro quest	46 months	311	0.4	1.0		

Table 3 continued

Study	Athletes	Study design	Study duration	Injuries (*n*)	Clinical incidence (injuries/lifter/years)	Injury incidence/rate (injuries/1000 h)	Sport injuries/1000 athlete exposures (1000 AEs)	Athlete rate (% injured)
Goertzen et al. [21]	240 open M	Retro quest and orthopedic exam	18 months	235	0.7			
Goertzen et al. [21]	118 open F	Retro quest and orthopedic exam	18 months	53	0.3			
Siewe et al. [31]	54 M, 17 F open, elite	Retro quest	EC	NS	0.12	0.24 [h]		45
Xiaojun and Taotao [37]	104 elite 74 M, 30 F	Retro quest	12 months	180	1.8			
Strongman								
Winwood et al. [26]	213 low and high level M	Retro quest	12 months	257	1.6 and 0.4[i]	5.5		
Winwood et al. [26]	92 low level	Retro quest	12 months	NS	1.4 and 0.3[i]	5.4		
	82 high level	Retro quest	12 months	NS	1.5 and 0.5[i]	4.9		
Winwood et al. [26]	71 $\leq$ 105 kg	Retro quest	12 months	NS	1.6 and 0.3[i]	6.1		
	100 $>$ 105 kg	Retro quest	12 months	NS	1.6 and 0.5[i]	4.5		
Winwood et al. [26]	91 $\leq$ 30 years	Retro quest	12 months	NS	1.6 and 0.5[i]	5.5		
	82 $>$ 30 years	Retro quest	12 months	NS	1.5 and 0.3[i]	5.4		
Highland Games								
McLennan and McLennan [32]	45 elite, 125 amateur	Retro quest	120 months	729		7.5		
CrossFit								
Hak et al. [33]	93 M, 39 F, open	Retro quest	EC	186		3.1		
Weisenthal et al. [34]	231 M, 150 F, open	Retro quest	6 months	84				19[j]

EC study duration was the athlete's entire career for the sport, *F* female, *M* male, *NS* not stated, *Retro quest* retrospective questionnaire

[a] From subset of 27 resident lifters

[b] Data collected during an Olympic competition (16 or 17 days)

[c] % of athletes injured during the Olympic competition

[d] Acute and recurrent (respectively)

[e] Total number of injuries per lifter over unknown duration

[f] Data from 2000

[g] Data from 1995

[h] Values indicate injury rate

[i] Values indicate training injuries and competition injuries per lifter/per year (respectively)

[j] % of injuries over 6 months

Table 4 Summary of weight-training injuries by (in general) the most frequently anatomical locations

Study	Athletes	Study design	Number of injuries	Most frequently injured anatomical locations				
				Shoulder (%)	Lower back (%)	Knee (%)	Elbow (%)	Wrist/hand (%)
Weightlifting								
Calhoon and Fry [27]	Open elite (NS)	Prospective	560	18	23	19	3	10
Kim and Kim [24]	National M and F (NS)	Prospective	207	7	8	10	4	21
Konig and Biener [36]	121 M	Retro quest	202	22[a]	21	25	6	2
Kulund et al. [35]	80 M	Retro quest	111	23	7	23	10	23
Raske and Norlin [25][b]	50 open elite M	Retro quest	108	14	18	20	7	10
Raske and Norlin [25][c]	50 open non-elite M	Retro quest	98	22	18	18	9	5
Wang et al. [23]	195 open M	Retro quest	NS	15[d]	19	29	9[e]	20
Wang et al. [23]	70 open F	Retro quest	NS		18	32		17
Powerlifting								
Brown and Kimball [13]	71 junior novice M	Retro quest	98	6	50	8	6	4
Goertzen et al. [21]	39 open M	Retro quest and orthopedic exam	120	32	33[f]	10	13	6
Goertzen et al. [21]	21 open F	Retro quest and orthopedic exam	40	22	24[f]	28	10	10
Haykowsky et al. [29]	9 M and 2 F open elite blind	Retro quest	4	25	25		25	
Keogh et al. [20]	82 M and 19 F	Retro quest	118	36	24	9	11	
Keogh et al. [20]	82 M	Retro quest	98	34	24	10	9	
Keogh et al. [20]	19 F	Retro quest	20	45	20	0	20	
Keogh et al. [20]	36 national	Retro quest	50	42	20	10	10	
Keogh et al. [20]	65 international	Retro quest	68	32	27	9	12	
Raske and Norlin [25][a]	50 open elite M	Retro quest	114	26	15	12	7	2
Siewe et al. [31]	219 M and 26 F open and elite	Retro quest	NS	Most injured site[g]	2nd most injured site[g]	3rd most injured site[g]	4th most injured site[g]	6th most injured site[g]
Bodybuilding								
Eberhardt et al. [38]	250 open M	Retro quest	311	23	9	5	11	23
Goertzen et al. [21]	240 open M	Retro quest and orthopedic exam	235	34	10[a]	17	21	16
Goertzen et al. [21]	118 open F	Retro quest and orthopedic exam	53	29	14[a]	31	10	12
Siewe et al. [31]	54 M and 17 F open and elite	Retro quest	NS	2nd most injured site[g]	Most injured site[g]	5th most injured site[g]	4th most injured site[g]	7th most injured site[g]
Xiaojun and Taotao [37]	104 elite, 74 M and 30 F	Retro quest	180	Most injured site[g]	6th most injured site[g]			
Strongman								
Winwood et al. [26]	213 low and high level M	Retro quest	257	21	24	11	6	0.4

Table 4 continued

Study	Athletes	Study design	Number of injuries	Most frequently injured anatomical locations				
				Shoulder (%)	Lower back (%)	Knee (%)	Elbow (%)	Wrist/hand (%)
Highland Games								
McLennan and McLennan [32]	45 elite + 125 amateur	Retro quest	729	18	17[f]	17	14	11
CrossFit								
Hak et al. [33]	93 M and 39 F, open	Retro quest	186	26	20[f]	10	13[f]	10
Weisenthal et al. [34]	231 M and 150 F open	Retro quest	84	25	14	13	5	6

F female, *M* male, *NS* not stated, *Retro quest* retrospective questionnaire

[a] Shoulder girdle

[b] Data from 2000

[c] Data from 1995

[d] Combined data for males and female lifters

[e] Arm and elbow

[f] Entire vertebral column

[g] No percentage given, or percentage given based on whether athlete had an injury to that site in their entire career

of each of the sports. Typically, weightlifters, powerlifters, and strongman and perhaps Highland Games athletes lift heavier loads (at a higher percentage of one repetition maximum [1RM]) for fewer repetitions with longer rest periods between sets than bodybuilders or CrossFit athletes [41–45]. Further, there may often be considerable between-sport differences in the manner in which these exercises are commonly performed that may alter the relative loading and hence injury risk to various anatomical locations.

The possibly higher rate of knee injuries for weightlifters (10–32 %) compared with other weight-training sports (5–28 %) may reflect differences in the manner in which the squat (and their derivatives) is performed by these groups. For example, weightlifters perform the clean and jerk, snatch, front squat, and high-bar back squats through a full range of motion whereby the gluteals may come to rest on the calf musculature at the bottom of the lift. Such a range of motion and the bar position requires the weightlifter to maintain a vertical trunk position and utilize large degrees of dorsiflexion and anterior knee translation. This contrasts with powerlifters and strongman athletes who typically position the bar further down their back than the other groups during the squat, with this typically referred to as a low-bar squat [41, 44]. This low-bar squat results in a greater forward inclination of the trunk at the bottom of the lift than the high-bar/front squat favored by weightlifters [46]. By virtue of these differences in trunk inclination, dorsiflexion, and anterior knee translation, the high-bar or front squat has a larger knee resistance moment arm and smaller hip/lower back resistance moment arm than the low-bar squat. Such differences in resistance moment arms suggest that the high-bar or front squat may require greater knee extensor torques and produce greater mean compressive patellofemoral forces than low-bar squats [2, 46]. Therefore, the lower frequency of knee injuries for some of the weight-training sports, including powerlifting and strongman, compared with weightlifting may reflect the reduced mechanical stress that low-bar squats apply to the knee compared with high-bar or front squats.

Overall, the subtle differences in the most commonly injured anatomical locations of injury for the weight-training sports suggests that differences in exercise/event load, selection, and the actual technique and body positioning in a particular exercise/event can alter the mechanical stress placed on specific anatomical locations and therefore the subsequent injury risk. A detailed analysis of the injury-inciting events is outlined in Sect. 3.8.

3.4.2 Environmental Location

Only four studies documented the number of injuries that lifters experienced in competition [22, 24, 26, 28], with many studies combining data from training and competition. Junge et al. [28] found that 90 % of injuries ($n = 26$) reported by weightlifting athletes at the 2008 Summer Olympic Games occurred during competition [22]. This was higher than the 45 % of competition injuries ($n = 18$) reported by weightlifters in the 2012 Summer Olympic Games [22]. In contrast, Kim and Kim [24] reported that 1.5 % of the injuries ($n = 3$) reported by Korean weightlifting athletes over a 271-day period occurred during competition. Winwood et al. [26] found that strongman athletes experienced 1.6 ± 1.5 training injuries per athlete per year compared with 0.4 ± 0.7 competition injuries per athlete per year. While such findings would suggest that the risk of injury in training is greater than in competition, weight-training athletes will often train many hours per week but only compete a handful of times per year, meaning the training exposure is substantially greater than that of competition. To address these limitations, future studies should seek to report the training and competition injury data per 1000 h of training and competition exposure. Such an approach is warranted in that athletes in the weight-training sports (with the possible exception of bodybuilding) are generally subjecting their bodies to greater levels of musculoskeletal stress in a competitive environment than they are in a training environment.

Three studies also specifically recorded injuries that did not occur as a direct result of weight training [20, 27, 38]. Keogh et al. [20] observed that 13 and 15 % of the injuries reported by a group of 101 powerlifters resulted from cross-training (e.g., ball sports or cardiovascular training) or were of unknown origin, respectively. Calhoon and Fry [27] reported similar results, with 36 % of the weightlifting injuries recorded in the US Olympic Training Centre occurring outside of their regular weightlifting training sessions. In contrast, Eberhardt et al. [38] found that only 1 % of the injuries reported by 250 bodybuilders occurred during non-weight-training activities.

3.5 When Does Injury Occur?

3.5.1 Injury Onset

As seen in Table 5, only eight studies have reported data on injury onset in the weight-training sports [20, 22–28], with these studies conducted on weightlifting, powerlifting, and strongman athletes. These studies reported the onset for all injuries collectively, with no injury-onset data given for each anatomical location. While most of these studies recorded acute and chronic injuries, there were a number of exceptions. Two weightlifting studies only reported chronic injuries [28, 38], one weightlifting study only reported acute and recurrent injuries [24], and Keogh et al. [20] also incorporated acute-to-chronic or 'other' onset categories. With the exception of Wang et al. [23] and perhaps Kim and Kim [24], these studies suggest that weightlifting, powerlifting, and strongman athletes experienced a greater rate of acute (26–72 %) than chronic (25–50 %) onset injuries.

3.5.2 Chronometry

Only two studies directly examined the chronometry of injury in the weight-training sports [26, 37]. Winwood et al. [26] found that half (51 %) of the training injuries reported by strongman athletes occurred in the general preparation phase of their yearly training plan. Winwood et al. [26] also asked the participants to estimate the time their injuries occurred during training sessions and competitions, via a tertile classification system, i.e., early, mid, or late within a training session or competition. The most common time for a training injury was 'early' in the training session (36 % of all training injuries), whereas the most common time for competition injury was late in the competition (44 % of all competition injuries) [26]. Xiaojun and Taotao [37] found that nearly half of all injuries (49 %) reported by bodybuilders occurred in the 3 winter months, whereas only 9 % of injuries occurred in the three summer months.

The limited data on chronometry of weight-training injuries appear somewhat consistent with aspects of the literature for team sports. Specifically, team sport athletes may suffer more injuries during the final third (15 min) of each half of a football (soccer) match and during the pre-season than regular season [47, 48]. Collectively, the results found in the review and those from previous studies of team sports may suggest that fatigue and a lack of 'conditioning' are also possible risk factors for injury in the weight-training sports [47, 48].

3.6 What is the Outcome?

3.6.1 Injury Type

Nine studies provided data on the injury type experienced by weight-training athletes (see Table 6), with strains, tendinitis, and sprains generally the most common across the sports, with some minor exceptions. The three most common injury types for these sports were (in descending order) weightlifting (strains, sprains, and tendinitis), powerlifting (strains, tendinitis, and arthritis), bodybuilding (sprains, tendinitis, and cartilage degeneration), strongman (muscle strains, tendon injuries, and ligament sprains/tears), and Highland Games (tendinitis, strains, and cartilage damage). The results demonstrate that the three sports in which competition and training performance is based on lifting heavier loads than other competitors (weightlifting,

Table 5 Summary of onset of weight-training injuries

Study	Athletes	Study design	Number of injuries	Injury onset	
				Acute (%)	Chronic (%)
Weightlifting					
Calhoon and Fry [27]	Open elite (NS)	Prospective	560	60	30
Engebretsen et al. [22]	149 M and 103 F open elite	Prospective	44	NS	34
Junge et al. [28]	255 elite M and F	Prospective	43	NS	>40
Kim and Kim [24]	National M (NS)	Prospective	125	27	NS
Kim and Kim [24]	National F (NS)	Prospective	82	35	NS
Wang et al. [23]	195 open M and 70 open F	Retro quest	257	26	42
Powerlifting					
Keogh et al. [20]	82 M and 19 F	Retro quest	118	59	41
Keogh et al. [20]	82 M	Retro quest	98	61	39
Keogh et al. [20]	19 F	Retro quest	20	50	50
Keogh et al. [20]	36 national	Retro quest	50	72	28
Keogh et al. [20]	65 international	Retro quest	68	50	50
Raske and Norlin [25][a]	50 M and 10 F open elite PL 50 M and 5 F open elite WL	Retro quest	254	25	25
Strongman					
Winwood et al. [26]	174[b] low and high level M	Retro quest	258	68	31
Winwood et al. [26]	92[b] low level	Retro quest	136	68	33
Winwood et al. [26]	82[b] high level	Retro quest	121	69	31
Winwood et al. [26]	71[b] $\leq$ 105 kg	Retro quest	100	68	32
Winwood et al. [26]	100[b] > 105 kg	Retro quest	154	68	32
Winwood et al. [26]	91[b] $\leq$ 30 years	Retro quest	128	65	35
Winwood et al. [26]	82[b] > 30 years	Retro quest	129	72	28

F female, *M* male, *NS* not stated, *PL* powerlifters, *Retro quest* retrospective questionnaire, *WL* weightlifters

[a] Data from 2000 and consisting of a mixed group of PL and WL

[b] Number of injured athletes

powerlifting, and strongman) have muscle strains as the most common injury type (6–62 %). In contrast, bodybuilders who typically train at a lower percentage of 1RM experience a lower proportion of muscle injuries (7–34 %) but report a greater proportion of cartilage (28–32 %) and tendon injuries (29–63 %). Such results suggest that the greater loads used by powerlifters, weightlifters, and strongman athletes predispose them to a higher proportion of acute-type muscle strain injuries, with the greater volume of exercise performed by bodybuilders tending to produce a greater proportion of chronic-type connective tissue injuries.

3.6.2 Severity of Injury and Associated Time Loss

A total of 14 studies reported data on the injury severity/time loss associated with injuries, with a summary of these studies provided in Table 7. Two studies (both on powerlifting) reported that the average injury was symptomatic for ~12 days [13, 29]. A number of other studies also recorded the time that each injury affected training but reported it in specific time bands, such as <1 day, 1–7 days, 8–14 days, and >14 or 30 days (1 month) [22, 25, 27, 32, 35, 36]. With the exception of Raske and Norlin [25], all of the studies reporting data on severity/time loss of injury indicated that the majority of weight-training injuries were symptomatic for less than 2 weeks, a value similar to the two powerlifting studies reporting mean injury durations of 12 days [13, 29]. Another four studies [20, 23, 26, 37] assessed the time loss by categorizing the effect the injury had on the athletes' training, with injuries classified as mild (exercise execution required modification), moderate (stopped performing the exercise), or major (training stopped completely for a period of at least a week). In general, these four studies also observed most injuries (78–99 %) to be mild or moderately severe.

3.6.3 Clinical Outcome

The clinical outcome of injury can be described using a variety of outcomes, including recurrent (repeat) injury, catastrophic incidents, non-participation injury (injuries

Table 6 Summary of most common types of weight training injuries

Study	Athletes	Study design	Number of injuries	Injury type				
				Arthritis (%)	Cartilage damage/degeneration (%)	Sprain (%)	Strain (%)	Tendinitis (%)
Weightlifting								
Calhoon and Fry [27]	Open elite (NS)	Prospective	560			13	45	24
Konig and Biener [36]	121 M	Retro quest	202		3	39	29	
Powerlifting								
Brown and Kimball [13]	71 junior novice M	Retro quest	98			4	62	12
Goertzen et al. [21]	39 open M	Retro quest and orthopedic exam	120	29	17	6	6	28
Goertzen et al. [21]	21 open F	Retro quest and orthopedic exam	40	17	9	17	11	25
Haykowsky et al. [29]	9 M and 2 F open elite blind	Retro quest	4				Most common injury type[a]	
Bodybuilding								
Eberhardt et al. [38]	250 open M	Retro quest	311			39	10[b]	
Goertzen et al. [21]	240 open M	Retro quest and orthopedic exam	235	18	32	6	7	23
Goertzen et al. [21]	118 open M	Retro quest and orthopedic exam	53	8	28	13	8	33
Xiaojun and Taotao [37]	104 elite 74 M and 30 F	Retro quest	180	3[c]		63	34	
Strongman								
Winwood et al. [26]	174[d] low and high level M	Retro quest	174		3.5	7[e]	38	23[f]
Highland Games								
McLennan and McLennan [32]	45 elite + 125 amateur	Retro quest	729	3	13	4	26 [g]	38

F female, *M* male, *NS* not stated, *Retro quest* retrospective questionnaire

[a] Percentage not stated

[b] Includes muscle/joint injuries

[c] Bone-related injuries

[d] Number of injured athletes

[e] Ligament sprain/tear

[f] Includes tendon strains/tears

[g] Includes musculoligamentous injuries to the back (14 %)

Table 7 Summary of severity/time loss of weight-training injuries

Study	Athletes	Study design	Number of injuries	Severity/time loss			
				Mild injury (%)	Moderate injury (%)	Major injury (%)	Time loss/injury (%)
Weightlifting							
Calhoon and Fry [27]	Open elite (NS)	Prospective					99 all injuries $\leq$7 days
Engebretsen et al. [22]	149 M and 103 F open elite	Prospective	44				43 $\geq$ 1 day, 25 $\geq$ 7 days
Junge et al. [28]	255 open elite M and F	Prospective	43				11.4 % athletes with time loss injuries[a]
Konig and Biener [36]	121 M	Retro quest	202				82 knee and 76 shoulder injuries $\leq$7 days
Kulund et al. [35]	80 M	Retro quest	111				57 all injuries $\leq$14 days
Wang et al. [23]	195 open M and 70 open F	Retro quest	257	45	55	1	
Powerlifting							
Brown and Kimball [13]	71 junior novice M	Retro quest	98				12 days
Haykowsky et al. [29]	9 M and 2 F open elite blind	Retro quest	4				12 days
Keogh et al. [20]	82 M and 19 F	Retro quest	118	39	39	22	
Keogh et al. [20]	82 M	Retro quest	98	36	38	24	
Keogh et al. [20]	19 F	Retro quest	20	50	40	10	
Keogh et al. [20]	36 national	Retro quest	50	40	42	18	
Keogh et al. [20]	65 international	Retro quest	68	38	37	25	
Raske and Norlin [25][b]	50 M and 10 F open elite PL, 50 M and 5 F open elite WL	Retro quest	254				93 shoulder, 85 lower back and 80 knee injuries >30 days
Bodybuilding							
Xiaojun and Taotao [37]	104 elite, 74 M and 30 F	Retro quest	180	59	28	13	
Strongman							
Winwood et al. [26]	174[c] low and high level M	Retro quest	261	33	47	20	
Winwood et al. [26]	92[c] low level	Retro quest	138	32	51	17	
Winwood et al. [26]	82[c] high level	Retro quest	122	31	43	25	
Winwood et al. [26]	71[c] $\leq$ 105 kg	Retro quest	92	21	53	26	
Winwood et al. [26]	100[c] > 105 kg	Retro quest	85	35	47	18	
Winwood et al. [26]	91[c] $\leq$ 30 years	Retro quest	130	41	45	15	
Winwood et al. [26]	82[c] > 30 years	Retro quest	129	25	50	26	
Highland Games							
McLennan and McLennan [32]	45 elite + 125 amateur	Retro quest	729				67 all injuries $\leq$7 days
CrossFit							
Hak et al. [33]	93 M and 39 F, open	Retro quest	186				7 all injuries required surgery

F female, *M* male, *NS* not stated, *PL* powerlifters, *Retro quest* retrospective questionnaire, *WL* weightlifters

[a] Length of time loss not stated

[b] Data from 2000

[c] Number of injured athletes

that force the athlete to retire), and residual effects (injuries resulting in long-lasting or permanent symptoms or disability) [11]. Results of this review indicate there is little clinical outcome epidemiological data specifically determined for the weight-training sports.

Winwood et al. [26] reported that 115 (44 %) of the 260 injuries reported by strongman athletes over the course of the year were repeated (recurrent) injuries. Kim and Kim [24] reported that 145 (70 %) of the 207 injuries reported by Korean weightlifters were recurrent injuries. In contrast, Kulund et al. [35] reported that only three of the 111 injuries reported by a group of 80 weightlifters were recurrent; however, unfortunately, this study was limited in that the duration over which data collection occurred was not stated.

Some insight into the potential of the weight-training sports to result in non-participation injuries was obtained by Raske and Norlin [25]. Over the course of 5 years of data collection, they reported that 38 % of the elite weightlifters and powerlifters retired, with almost half (43 %) of these lifters citing injury as the reason for retiring [25]. Such results may suggest that participation in the weight-training sports has the potential to lead to a range of residual effects that may affect these athletes after retirement. This view is supported by the findings that arthritis (3–29 %) and cartilage degeneration (13–32 %) are some of the most commonly reported injuries in powerlifting, bodybuilding, and Highland Games [21, 32]. A review by Kujala et al. [49] also supports this view, whereby power athletes (defined as weightlifters, wrestlers, boxers and track and field sprinters, jumpers, and throwers) had a risk ratio (RR) of 2.68 for developing arthritis of the hip, knee, and ankle compared with sedentary controls. However, similar risks of arthritis were also found for endurance (RR 2.37) and team sports (RR 2.42) athletes. This suggests that, while high-level sports participation may increase the risk of arthritis in later life, the weight-training sports do not impose greater risks than those found in endurance and team sports.

Currently, no injury epidemiology studies have assessed the rate of acute catastrophic incidents. Therefore, it is unclear how frequent such catastrophic incidents may be in the different weight-training sports and how these might be affected by a variety of intrinsic and extrinsic factors. However, the case study literature does indicate that the potential for catastrophic incident exists in the weight-training sports, with the possibility of serious injury and even death [8, 9].

3.6.4 Economic Cost

No economic cost data appear to have been reported in any of the weight-training injury epidemiology studies to date, even though there exists the potential for weight training to have economic costs related to the pain, discomfort, and disability the athletes may experience [50, 51]. Some insight into the economic cost of injuries may be obtained from outcomes, including the cost of injury-related treatment during the athletes' competitive years, the duration and nature of injury-related treatment after retiring as well as the loss of school or work time associated with injury. Although the economic cost of injury in the weight-training sports did not appear to be reported in any of the studies eligible for inclusion in this review, the potential for weight training to result in residual adverse effects that may have economic costs during the athletes' competitive careers and retirement has been examined in the wider sports injury literature [49]. However, the results of a systematic review and meta-analysis suggest that participation in the weight-training sports may be somewhat cost neutral or even beneficial. Specifically, Kujala et al. [49] reported that cardiovascular disease risk was reduced or similar in retired endurance (RR 0.24–0.73), team (RR 0.48–0.86), and power sport (RR 0.49–0.94) athletes compared with sedentary controls. Similar results were observed for hospital utilization rates, whereby endurance, team, and power sport athletes had RRs of 0.71, 0.86, and 0.95 compared with sedentary controls, respectively [49].

3.7 What are the Risk Factors?

A variety of potential extrinsic and intrinsic risk factors may predispose athletes to injury in the weight-training sports. Identification of the relevant modifiable risk factors may therefore allow specific injury-prevention programs to be tailored to these weight-training sports; whereas a description of relevant non-modifiable risk factors may be useful for individuals who are considering participating in these sports.

3.7.1 Intrinsic Factors

Several studies of weight-training athletes have examined the effect of intrinsic factors, including sex [20–24], competitive standard (e.g., high and low level) [20, 23, 25, 26], age (e.g., open vs. masters) [20, 26], and bodyweight class (e.g., lightweight vs. heavyweight) [20, 26] on the injury epidemiology of the weight-training sports. In general, these intrinsic factors had relatively little effect on the injury epidemiology of the weight-training sports. The exceptions to this generalization are described below.

Where significant sex differences were observed, these exceptions suggested that female lifters had significantly lower overall injury rates (1.3 vs. 2.1 injuries per lifter per year) [21], a lower rate of recurrent injuries (173 vs. 362 injuries per 1000 h of exposure) [24], a significantly lower rate of acute injuries (50 vs. 61 %) [20], a significantly higher rate of knee injuries (28–32 vs. 10–29 %) [21, 23], and a significantly lower rate of chest (0 vs. 4 %) and thigh (0 vs. 7 %) injuries [20] than their male counterparts. While the potential mechanisms contributing to the relatively small number of sex-related differences in aspects of their injury epidemiology are not well understood, female lifters' higher rate of knee injuries appears consistent with some findings for other sports and activities [52].

For the studies reporting significant differences between elite (international) and non-elite (national) lifters, elite lifters had a significantly lower rate of injuries (3.6 vs. 5.8 injuries per 1000 h) and acute injuries (50 vs. 72 %) than non-elite lifters [20]. Elite lifters also had significantly fewer chest (0 vs. 8 %) and shoulder injuries (32 vs. 42 %) but significantly more thigh injuries (10 vs. 0 %) than non-elite lifters [20].

For studies comparing the effect of age and bodyweight class, a significantly greater rate of competition injuries per athlete per year were reported among younger (≤30 years) than among older (>30 years) strongman athletes (0.5 vs. 0.3 injuries per year), as well as in heavyweight (>105 kg) than in lightweight competitors (≤105 kg) (0.5 vs. 0.3 injuries per year) [26]. Some significant age-related and bodyweight class-related differences were also observed for the severity of strongman injury [26]. Interestingly, despite the heavier loads that these athletes train and compete with, the >105-kg strongman athletes had proportionally less severe (18 vs. 26 %) and moderate injuries (47 vs. 53 %) than the ≤105-kg athletes. Older strongman athletes (aged >30 years) also experienced almost twice as many severe injuries (26 vs. 15 %) as the group aged ≤30 years.

While based on a limited number of peer-reviewed studies, it appears that the intrinsic factors of sex, competitive standard, and age and bodyweight class may have only a relatively minor influence on the injury epidemiology of the weight-training sports. This suggests that athletes of both sexes as well as a variety of competitive standards, ages and bodyweight classes may participate in these activities with similar risks of injury.

3.7.2 Extrinsic Factors

Factors such as coaching, the rules of the sport, and the training environment could be extrinsic factors related to injury in the weight-training sports. However, no experimental studies have so far been conducted to examine this possibility for the weight-training sports.

3.8 What are the Inciting Events?

Several studies included in this review attempted to gain insight into events that may contribute to injury in weight-training sports [23, 26, 37, 38]. As an example, Wang et al. [23] sought to determine the inciting events that weightlifters thought contributed to injury. Weightlifters felt that 60 % of their injuries were associated with tiredness (fatigue), 31 % were associated with technical errors, and 21 % with excessive overload. The bodybuilders in the study by Xiaojun and Taotao [37] felt that 21 % of their injuries were caused by fatigue (and poor recovery), 18 % by training with overly heavy loads, and 14 % by insufficient preparation (i.e., warm up). Bodybuilders in the Eberhardt et al. [38] study felt their injuries were a result of improper warm-up (42 %), too vigorous exercising (35 %), or by lack of "guarding assistance", better known as appropriate spotting by training partners (7 %). Strongman athletes cited poor technique as the most frequent contributing factor to injury (25 %), with a wide variety of other minor inciting events also influencing injury [26].

Unfortunately, the validity of the relatively limited inciting event data for the weight-training sports appears questionable for several reasons. These include (1) the retrospective design of the studies, (2) the relative lack of clear definitions within and between studies for an inciting event, and (3) the self-report nature of the data. Notwithstanding these limitations, fatigue has previously been implicated as an inciting factor to sporting injury [47, 48]. Lifters may therefore need to perform the most demanding, challenging, and high-risk exercises during the initial part of their training sessions to help minimize their risk of injury.

Nine studies have also sought to examine the inciting factors to injury by determining which exercises/events/disciplines are most associated with injury [20, 25, 26, 30–32, 34, 35, 38] (see Table 8). Keogh et al. [20] and Siewe et al. [30] reported that the squat, deadlift, and bench press were the most common injury-causing exercises for powerlifters (31–61 %). Kulund et al. [35] found the clean and jerk, squat, and snatch were the three most commonly cited injury-causing exercises for weightlifters (21–46 %). In contrast, the squat (11–24 %), bench press (6–16 %), and shoulder press (9–14 %) were the most common injury-causing exercises for bodybuilders [31, 38] and strongman athletes [26]. For CrossFit athletes, powerlifting, gymnastics, and Olympic lifting exercises (23, 20, and 17 %, respectively) were most commonly cited as causing injury [34]. McLennan and McLennan [32] observed that the weight toss, caber toss, and hammer throw (31, 25, and 20 %, respectively) accounted for most Highland Games event injuries, with no data available on the injuries attributable to the weight training.

The results of these studies on the inciting events for the weight-training sports are of some interest but only go so far into describing the factors contributing to injury in these sports. The reason for this is that the most common

Table 8 Summary of injury causation by training type and/or event

Study	Athletes	Study design	Injuries (*n*)	Training type/event	Number and/or percentage of injuries/reported pain
Weightlifting					
Kulund et al. [35]	80 M	Retro quest	111	Clean and jerk	51 (46 %)
				Deep squats	25 (23 %)
				Snatch	23 (21 %)
				Deadlift	7 (6 %)
				Press	5 (5 %)
Powerlifting					
Keogh et al. [20]	82 M and 19 F	Retro quest	118	Squat/deadlift/bench press	52 %
				Assistance exercises	20 %
				Cross training	13 %
				Unknown	15 %
Siewe et al. [30]	54 M and 17 F open and elite	Retro quest		Squat	65 (61 %)[a]
				Bench Press	60 (57 %)[a]
				Deadlift	33 (31 %)[a]
				Others	43 (41 %)[a]
Raske and Norlin [25]	50 M and 10 F open elite PL; 50 M and 5 F open elite WL	Retro quest	254	Bench Press	43 and 44 %[b]
				Flies	47 and 52 %[b]
				Dips	36 and 39 %[b]
				Snatch	33 and 31 %[b]
				Clean and Jerk	33 and 31 %[b]
Bodybuilding					
Eberhardt et al. [38]	250 open M	Retro quest	311	Bench press	16 %
				Shoulder press	14 %
				Squat	11 %
				Others	59 %
Siewe et al. [31]	54 M and 17 F open and elite	Retro quest		Squat	17 (24 %)[a]
				Bench press	9 (13 %)[a]
				Deadlift	4 (6 %)[a]
				Others	30 (42 %)[a]
Strongman					
Winwood et al. [26]	174[c] low and high level M	Retro quest	268	Traditional training	145 (54 %)
				Deadlift	47 (18 %)
				Squats	42 (16 %)
				Overhead press	24 (9 %)
				Bench press	16 (6 %)
				Traditional other	16 (6 %)
				Strongman training	123 (46 %)
				Stone work	24 (9 %)
				Yoke walk	21 (8 %)
				Tire flip	16 (6 %)
				Farmers walk	12 (5 %)
				Axle work	11 (4 %)
				Log lift/press	11 (4 %)
				Strongman other	28 (10 %)

Table 8 continued

Study	Athletes	Study design	Injuries (*n*)	Training type/event	Number and/or percentage of injuries/reported pain
Highland Games					
McLennan and McLennan [32]	45 elite + 125 amateur	Retro quest	729	Highland Games event	
				Weight toss	31 %
				Caber toss	25 %
				Hammer throw	20 %
				Stone throw	13 %
				Weight for height	11 %
CrossFit					
Weisenthal et al. [34]	231 M and 150 F, open	Retro quest	84	Crossfit movement type	
				Powerlifting	19 (23 %)
				Gymnastics	17 (20 %)
				Olympic lifting	14 (17 %)
				Endurance	5 (6 %)
				Other	13 (15 %)

M male, *F* female, *PL* powerlifters, *WL* weightlifters, *Retro quest* retrospective questionnaire

[a] Reported pain as a result of the exercise

[b] Weight-training exercise and shoulder injury association from 1995 and 2000 (respectively)

[c] Number of injured athletes

inciting-event exercises were typically the competitive events in the sports (i.e., powerlifting, weightlifting, and Highland Games). As such, these exercises were likely to be performed more frequently in training and competition than other exercises and hence be more highly associated with injury. This relationship between exercise frequency (exposure) and injury risk was also observed among strongman competitors. Specifically, strongman athletes reported that the six most commonly performed exercises (farmer's walk, log press, stones, tire flip, axle clean and press, and yoke walk) [41] accounted for 77 % of all injuries reported during event-specific strongman training [26]. Future studies will need to calculate the relative exposure of the most common exercises to better identify which exercises may be inherently more risky than others.

4 Conclusion

Results of the 20 studies included in this systematic review suggest that most of the weight-training sports have injury rates of ~1–2 injuries per athlete per year and ~2–4 injuries per 1000 h of training/competition exposure. The majority of injuries reported in these studies were of minor or moderate severity and affected the shoulder, lower back, and knee. While the injury epidemiology was relatively similar across the six weight-training sports, Highland Games (7.5 injuries per 1000 h) and strongman (5.5 injuries per 1000 h) appeared to have higher rates of injury than the other four sports. While many between-sport similarities in injury epidemiology were observed, each of the weight-training sports tended to have some subtle differences in the proportional injury rates across the various anatomical locations as well as across the onset and severity of injury. Additional research is required to substantiate the magnitude of these between-sport comparisons, particularly in strongman and Highland Games, each of which had only one injury epidemiology study included in this review. While we acknowledge that the 20 studies included in this systematic review is a very small sample compared with samples for other sporting activities, the injury rate of the weight-training sports appears considerably smaller than many other commonly performed sports. For example, recent studies on soccer, rugby union, and cricket have reported ~15–81 injuries per 1000 h [53–55]. Such comparisons suggest that participation in the weight-training sports results in fewer injuries than participation in many other popular team sports.

As the weight-training sports are performed by a wide variety of people of different ages, sexes, competitive standards, and bodyweight classes, additional research should also focus on direct comparisons between these subgroups of weight-training athletes. Further cohort studies also need to be conducted to determine how other intrinsic factors, e.g., anthropometric profile, flexibility, and muscular strength/endurance imbalances [56–59]; extrinsic factors, e.g., use of weight belts [60, 61]; and inciting events, e.g., fatigue, exercise technique, and selection [62–64] may modulate the injury risk. Such studies will inform the development of research-based injury-prevention programs that can then be tested for their efficacy in randomized controlled trials, similar to those conducted for sports such as soccer and handball [65].

Considerable improvements in the standard of injury epidemiology research for the weight-training sports are also required. Currently, many of the studies included in this review only reported data for a subset of the variables recommended by the IOC for a full understanding of the epidemiology of sporting injury [11]. In particular, environmental location, onset, chronometry, clinical outcome, and economic cost were infrequently (if at all) reported in the eligible studies. Greater detail on the training performed by each athlete (e.g., training frequency, number of set and repetitions, exercise performed, and loads used) for each week's training would also be most useful. Such data (if involving a large enough sample of randomly selected athletes over a sufficient period of time) may allow some insight into how alterations in the training program may influence the rate of injury in these sports. A reduction in the ROB should also be a focus of future research, with current studies primarily limited by their study design, participant inclusion, duration of data collection, confirmation of injury diagnosis, and changes in risk exposure. We recommend that future studies utilize prospective research designs and the participants be followed for a minimum of 6 months. The generalizability of results would be improved if the invited participants were randomly selected from the available populations. It would also be useful to confirm injury diagnosis via medical examination. While a medical examination may be difficult to include in the retrospective designs commonly used in the literature, future prospective studies could more easily utilize a medical examination to increase the validity of the data, especially for injury type [66]. This type of research may be most easily conducted at institutes of sport and national and Olympic training centers as Calhoon and Fry [27] and Kim and Kim [24] did, or at specific competitions such as Olympic Games [22, 28].

In conclusion, the weight-training sports appeared to have relatively similar injury epidemiology characteristics, regardless of the age, sex, bodyweight class, or competitive standard of the athlete. The injury rates for the weight-training sports appeared considerably lower than those reported for many team sports. However, the ROB assessment performed in this review suggests greater methodological rigor is required in future weight-training sport injury epidemiology studies to confirm the relative safety of the weight-training sports.

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References

1. Cholewicki J, McGill SM, Norman RW. Lumbar spine loads during the lifting of extremely heavy weights. Med Sci Sports Exerc. 1991;23(10):1179–86.
2. Escamilla RF, Fleisig GS, Lowry TM, et al. A three-dimensional biomechanical analysis of the squat during varying stance widths. Med Sci Sports Exerc. 2001;33(6):984–98.
3. Escamilla RF, Fleisig GS, Zheng N, et al. Biomechanics of the knee during closed kinetic chain and open kinetic chain exercises. Med Sci Sports Exerc. 1998;30(4):556–69.
4. Escamilla RF, Francisco A, Fleisig GS, et al. A three-dimensional biomechanical analysis of sumo and conventional style deadlifts. Med Sci Sports Exerc. 2000;32(7):1265–75.
5. McGill SM, McDermott A, Fenwick CMJ. Comparison of different strongman events: trunk muscle activation and lumbar spine motion, load, and stiffness. J Strength Cond Res. 2009;23(4):1148–61.
6. Gill IP, Mbubaegbu C. Fracture shaft of clavicle, an indirect injury from bench pressing. Br J Sports Med. 2004;38(5):E26.
7. George SM. Simultaneous acute rotator cuff tear and distal biceps rupture in a strongman competitor. Orthop. 2010;16:268–70.
8. George DH, Stakiw K, Wright CJ. Fatal accident with weight-lifting equipment: implications for safety standards. Can Med Assoc J. 1989;140(8):925–6.
9. Luke JL, Farb A, Virmani R, et al. Sudden cardiac death during exercise in a weight lifter using anabolic androgenic steroids: pathological and toxicological findings. J Forensic Sci. 1990;35(6):1441–7.
10. National Center for Catastrophic Sport Injury Research. 2016. Definition. In: Catastrophic injury. http://nccsir.unc.edu/definition-of-injury/. Accessed 13 May 2016.
11. Caine D, Harmer P, Schiff M. Preface. In: Caine D, Harmer P, Schiff M, editors. The encyclopaedia of sports medicine: the epidemiology of injury in Olympic sports. Oxford: Blackwell; 2009. p. xi–xiii.
12. Keogh JWL. Weightlifting. In: Caine D, Harmer P, Schiff M, editors. The encyclopaedia of sports medicine: the epidemiology of injury in Olympic sports. Oxford, England: Blackwell; 2009. p. 336–50.
13. Brown EW, Kimball RG. Medical history associated with adolescent powerlifting. Pediatrics. 1983;72(5):636–44.
14. Malina RM. Weight training in youth-growth, maturation, and safety: an evidence-based review. Clin J Sport Med. 2006;16(6):478–87.
15. Faigenbaum AD, Kraemer WJ, Blimkie CJR, et al. Youth resistance training: updated position statement paper from the national strength and conditioning association. J Strength Cond Res. 2009;23(S5):S60–79.
16. Lloyd RS, Faigenbaum AD, Stone MH, et al. Position statement on youth resistance training: the 2014 International Consensus.

Br J Sports Med. 2014;48(7):498–505. doi:10.1136/bjsports-2013-092952.

17. Lopes AD, Hespanhol LCJ, Yeung SS, et al. What are the main running-related musculoskeletal injuries? A systematic review. Sports Med. 2012;42(10):891–905.
18. Kluitenberg B, van Middelkoop M, Diercks R, et al. What are the differences in injury proportions between different populations of runners? A systematic review and meta-analysis. Sports Med. 2015;45(8):1143–61.
19. Nauta J, Martin-Diener E, Martin BW, et al. Injury risk during different physical activity behaviours in children: a systematic review with bias assessment. Sports Med. 2014;45(3):327–36. doi:10.1007/s40279-014-0289-0.
20. Keogh J, Hume PA, Pearson S. Retrospective injury epidemiology of one hundred one Oceania competitive power lifters: the effects of age, body mass, competitive standard, and gender. J Strength Cond Res. 2006;20(3):672–81.
21. Goertzen M, Schoppe K, Lange G, et al. Injuries and damage caused by excess stress in body building and power lifting. Sportverletz Sportsc. 1989;3(1):32–6.
22. Engebretsen L, Soligard T, Steffen K, et al. Sports injuries and illnesses during the London Summer Olympic Games 2012. Br J Sports Med. 2013;47:407–14.
23. Wang WY, Shi HF, Zuo H, et al. An epidemiological survey and comparative study of the injuries in weightlifting. Sports Sci. 2000;4:44–6.
24. Kim EK, Kim TG. Analysis of sports injuries among Korean national players during official training. J Korean Data Inf Sci Soc. 2014;25(3):555–65.
25. Raske A, Norlin R. Injury incidence and prevalence among elite weight and power lifters. Am J Sports Med. 2002;30(2):248–56.
26. Winwood PW, Hume PA, Cronin JB, et al. Retrospective injury epidemiology of strongman athletes. J Strength Cond Res. 2014;28(1):28–42.
27. Calhoon G, Fry AC. Injury rates and profiles of elite competitive weightlifters. J Athl Train. 1999;34(3):232–8.
28. Junge A, Engebretsen L, Mountjoy ML, et al. Sports injuries during the Summer Olympic Games 2008. Am J Sports Med. 2009;37(11):2165–72.
29. Haykowsky MJ, Warburton DER, Quinney HA. Pain and injury associated with powerlifting training in visually impaired athletes. J Vis Impair Blind. 1999;93:236–41.
30. Siewe J, Rudat J, Rollinghoff M, et al. Injuries and overuse syndromes in powerlifting. Int J Sports Med. 2011;32:703–11.
31. Siewe J, Marx G, Knoll P, et al. Injuries and overuse syndromes in competitive and elite bodybuilding. Int J Sports Med. 2014;35(11):943–8.
32. McLennan JG, McLennan JE. Injury patterns in Scottish heavy athletics. Am J Sports Med. 1990;18(5):529–32.
33. Hak PT, Hodzovic E, Hickey B. The nature and prevalence of injury during CrossFit training. J Strength Cond Res. Epub 22 November 2013.
34. Weisenthal BM, Beck CA, Maloney MD, et al. Injury rate and patterns among CrossFit athletes. Orthop J Sports Med. 2014;2(4):2325967114531177. doi:10.1177/2325967114531177.
35. Kulund DM, Dewey JB, Brubaker CE, et al. Olympic weightlifting injuries. Phys Sportsmed. 1978;6:111–8.
36. Konig M, Biener K. Sport-specific injuries in weight lifting. Schweiz Z Sportmed. 1990;38(1):25–30.
37. Xiaojun Z, Taotao LI. Sport injury law and preventing methods of Chinese elite bodybuilding players. J Shenyang Inst Phys Educ. 2008;27(4):75–7.
38. Eberhardt A, Dzbański P, Fabirkiewicz K, et al. Frequency of injuries in recreational bodybuilding. Phys Educ Sport. 2007;51:40–4.
39. Kolber MJ, Beekhuizen KS, Cheng MS, et al. Shoulder injuries attributed to resistance training: a brief review. J Strength Cond Res. 2010;24(6):1696–704. doi:10.1519/JSC.0b013e3181dc4330.
40. Neviaser TJ. Weight lifting: risks and injuries to the shoulder. Clin Sports Med. 1991;10(3):615–21.
41. Winwood PW, Keogh JWL, Harris NK. The strength and conditioning practices of strongman competitors. J Strength Cond Res. 2011;25(11):3118–28.
42. Fleck SJ, Kraemer WJ. Designing resistance training programs. 2nd ed. Champaign: Human Kinetics; 1997.
43. Kraemer WJ, Koziris LP. Olympic weightlifting and powerlifting. In: Lamb DR, Knuttgen HG, Murray R, editors. Physiology and nutrition for competitive sport. Carmel: Cooper; 1994. p. 1–54.
44. Swinton PA, Lloyd R, Agouris I, et al. Contemporary training practices in elite British powerlifters: survey results from an international competition. J Strength Cond Res. 2009;23(2):380–4.
45. Stone MH, Pierce KC, Sands WA, et al. Weightlifting: program design. Strength Cond J. 2006;28(2):10–7.
46. Wretenberg P, Feng Y, Arborelius UP. High- and low-bar squatting techniques during weight-training. Med Sci Sports Exerc. 1996;28(2):218–24.
47. Gabbett TJ, Domrow N. Relationships between training load, injury, and fitness in sub-elite collision sport athletes. J Sports Sci. 2007;25(13):1507–19.
48. Hawkins RD, Fuller CW. A prospective epidemiological study of injuries in four English professional football clubs. Br J Sports Med. 1999;33(3):196–203.
49. Kujala UM, Marti P, Kaprio J, et al. Occurrence of chronic disease in former top-level athletes. Predominance of benefits, risks or selection effects? Sports Med. 2003;33(8):553–61.
50. Granhed H, Morelli B. Low back pain among retired wrestlers and heavyweight lifters. Am J Sports Med. 1988;16(5):530–3.
51. Mundt DJ, Kelsey JL, Golden AL, et al. An epidemiologic study of sports and weight lifting as possible risk factors for herniated lumbar and cervical discs. Am J Sports Med. 1993;21(6):854–60.
52. Hughes G, Watkins J. A risk-factor model for anterior cruciate ligament injury. Sports Med. 2006;36(5):411–28.
53. Clausen MB, Zebis MK, Moller M, et al. High injury incidence in adolescent female soccer. Am J Sports Med. 2014;42(10):2487–94. doi:10.1177/0363546514541224.
54. Williams S, Trewartha G, Kemp S, et al. A meta-analysis of injuries in senior men's professional rugby union. Sports Med. 2013;43(10):1043–55. doi:10.1007/s40279-013-0078-1.
55. Orchard J, James T, Kountouris A, et al. Changes to injury profile (and recommended cricket injury definitions) based on the increased frequency of Twenty20 cricket matches. Open Access J Sports Med. 2010;1:63–76.
56. Barlow JC, Benjamin BW, Birt PJ, et al. Shoulder strength and range-of-motion characteristics in bodybuilders. J Strength Cond Res. 2002;16(3):367–72.
57. Gross ML, Brenner SL, Esformes I, et al. Anterior shoulder instability in weight lifters. Am J Sports Med. 1993;21(4):599–603. doi:10.1177/036354659302100419.
58. Keogh JWL, Hume PA, Pearson SN, et al. Can absolute and proportional anthropometric characteristics distinguish stronger and weaker powerlifters? J Strength Cond Res. 2009;23(8):2256–65.
59. Keogh JWL, Hume PA, Pearson SN, et al. Anthropometric dimensions of male powerlifters of varying body mass. J Sport Sci. 2007;25(2):1365–76.
60. Kraus JF, Schaffer KB, Rice T, et al. A field trial of back belts to reduce the incidence of acute low back injuries in New York City home attendants. Int J Occup Med Environ Health. 2002;8(2):97–104.

61. Reddell CR, Congleton JJ, Huchingson DR, et al. An evaluation of a weightlifting belt and back injury prevention training class for airline baggage handlers. Appl Ergon. 1992;23(5):319–29.
62. Fees M, Decker T, Snyder-Mackler L, et al. Upper extremity weight-training modifications for the injured athlete. A clinical perspective. Am J Sports Med. 1998;26(5):732–42.
63. McGill SM. Ultimate back fitness and performance. Waterloo: Wabuno Publishers; 2004.
64. Gabbett TJ. Incidence, site, and nature of injuries in amateur rugby league over three consecutive seasons. Br J Sports Med. 2000;34(2):98–103. doi:10.1136/bjsm.34.2.98.
65. Parkkari J, Kujala UM, Kannus P. Is it possible to prevent sports injuries? Review of controlled clinical trials and recommendations for future work. Sports Med. 2001;31(14):985–95.
66. Gabbe BJ, Finch CF, Bennell KL, et al. How valid is a self reported 12 month sports injury history? Br J Sports Med. 2003;37:545–7.