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A SYSTEMS-BASED APPROACH TO INJURY PREVENTION FOR THE STRENGTH AND CONDITIONING COACH

1 **ABSTRACT**

2 Participation in sport exposes athletes to an inherent risk of injury. In order to
3 develop a comprehensive injury prevention program, strength and conditioning
4 coaches must conduct a thorough needs analysis to establish the risk of injury,
5 identify mechanisms and risk factors for injury, select relevant screening tests
6 and design targeted interventions based on the athlete's results. Using a
7 systems-based approach presented herein, this article provides an overview of
8 the process that coaches must undertake in order to develop effective injury
9 prevention programs.

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1 **INTRODUCTION**

2 With sports participation, there is an inherent risk of injury that is unavoidable
3 (26); however, reducing the incidence of injuries is one of many priorities for
4 strength and conditioning (S&C) coaches alongside the development of
5 relevant physical qualities. In order to design an S&C program that enhances
6 performance whilst reducing injury risk, a thorough needs analysis should be
7 conducted for each athlete that is both relevant to the sport and the individual
8 (70).

9

10 Generic movement screening systems have previously been suggested as a
11 useful tool for identifying injury risk (43, 68) and have been employed by high
12 level professional organizations for the purpose of identifying athletes at risk of
13 injury (52). However, these methods demonstrate little capacity to identify injury
14 risk within large-scale studies with substantial sample sizes (5, 53, 57). This
15 may be due to deviations from their original design, which was to establish
16 foundational movement competency in non-specific activities (14), along with
17 many prospective cohort studies using sample sizes that are too small to
18 accurately identify risk factors (49). An approach focused on examining the
19 relevant movement patterns which are reflective of the demands of the sport
20 and mechanisms of injury, is likely to be required to prevent sports injuries (8).
21 More recently, the ability to predict injury has been questioned due to the multi-
22 factorial nature and unique circumstances that accompany an injury incident
23 (9). Nonetheless, the current body of evidence indicates that the application of
24 well-designed interventions, encompassing resistance training, plyometrics,

1 balance and skill training does reduce modifiable risk factors (39, 41, 59, 60),
2 and the subsequent reduction of injury risk (8).

3

4 The objective of this article is to provide S&C coaches with a systems-based
5 approach to reduce injury risk with their athletes, along with presenting an
6 example of how this model could be applied to enhance practical application.
7 This includes clear sequencing, whereby evidence-based screening tools are
8 used and the information gathered from this process will then allow coaches to
9 design injury prevention programs to target modifiable risk factors. This model
10 is based on the work of van Mechelen et al. (79) and Finch (25). Modifications
11 have been made for application in the setting of a S&C program. This approach,
12 which along with effective monitoring of the training program to manage the
13 distribution of load, has a greater potential to reduce an athlete's injury risk.

14

15 **CONSIDERATIONS FOR DEVELOPING AN INJURY PREVENTION MODEL**

16 Prior to the implementation of any training intervention, the S&C coach must
17 understand the demands of the sport and the athlete's ability to cope with those
18 requirements. Similar to the design of a performance program, a needs analysis
19 relevant to injury risk must be conducted (70). Using this information, a testing
20 battery can be designed and implemented in order to identify and reduce
21 modifiable baseline risk factors. Figure 1 illustrates this five-step process for
22 the injury prevention model. After discussing the five step process, a relevant
23 demonstration of how this process can be employed through a case study.

24

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INSERT FIGURE 1 HERE

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2 By applying this systems-based approach to designing and implementing an
3 injury prevention program, S&C coaches will be able to plan effective strategies
4 to reduce injury risk. In addition to accurate documentation of the occurrence
5 of athlete injuries, this approach will allow for the continual development of an
6 injury prevention program that can be refined and updated as new evidence
7 becomes available within both the literature and the coaches practice. It is
8 important to note that this approach must align with the development of the
9 athlete's physical and sports performance, and should rarely be seen as a
10 separate component. From this perspective, the injury prevention program is
11 viewed as an inclusive element to the training process that allows the athlete to
12 thrive in their sporting environment.

13

14 **STEP 1: ESTABLISH THE RISK OF INJURY THROUGH SPORTS**
15 **PARTICIPATION**

16 The first step in identifying the injury risk associated with a sport is to examine
17 the injury epidemiology in the literature (25). This allows coaches to establish
18 the injury incidence for any given sport, which represents the number of injuries
19 occurring relative to the time participating in either training or competition for
20 the sport, divided by the number of athletes included in the data collection
21 process (79). The major issue with this type of analysis is the manner in which
22 injuries are reported (24). Finch (25) suggests the following methodological
23 limitations exist within injury surveillance research:

24

25 1. The use of many injury survey's that have not been validated.

- 1 2. Recall bias present with retrospective data collection as athlete's report
- 2 injuries a long time following the onset of the injury.
- 3 3. Studies fail to define sports injury as well as severity.
- 4 4. Failing to report exposure to sport via training or competition as it relates
- 5 to injury incidence.

6

7 Although recent literature has accounted for many of these issues, coaches
8 must be sure to critically analyze the research that they use to inform their
9 model. Importantly, research used to inform the training process should include
10 validated measures for data collection, use of a prospective study design,
11 documentation of the severity of injuries by identifying days missed from sport
12 participation, and establish the athlete's exposure to training and competition.
13 For further details and observation of consensus statements for the undertaking
14 and examination of injury surveillance research, coaches should review the
15 following resources (28, 29, 42).

16

17 Alongside such considerations, coaches should also be sure to incorporate
18 research that is specific to the sport and their athletes profile in order for the
19 incidence data to be valid. For example, injury epidemiology research should
20 be evaluated based on the sex (36), age (74), player position (76), level of
21 competition (33, 34), and the era in which the data were recorded due to
22 potential rule changes or changes in sport demands (15, 35). Thus, research
23 used to inform the injury prevention model must be relevant to the athlete and
24 their sport for successful outcomes to be achieved.

25

1 Once injury incidence has been established, coaches must also consider the
2 severity of each injury in order to prioritize interventions (79). If only the
3 incidence is considered, coaches may mistakenly prioritize the prevention of
4 injuries that have a high frequency rate, yet lead to little time-loss from training
5 and competition. Instead, injuries that occur frequently and are associated with
6 an increased severity should be the major focus of screening assessments and
7 injury prevention training programs to minimize days-lost that could be used for
8 athlete development.

9

10 Severity of injury should also be considered in relation to the nature of the injury
11 (79), specifically as it relates to the type of tissue injured and the degree of
12 damage (i.e. grade I vs. III muscle strain). As muscle tissues receive a greater
13 blood supply than ligaments, tendon and cartilage, healing rate is expected to
14 be superior (58). As such, the prevention of ligament injuries may be prioritized
15 over muscle injuries if all other factors are equal. Severity may not only impact
16 the time-loss from sports training and competition, but also the demand for
17 treatment, cost of injury, as well as the potential for permanent damage that
18 may impact the athlete's long-term health (79). All variables should be factored
19 into the decision-making process in order to prioritize the development of a
20 relevant testing battery and implementation of a targeted training intervention.

21

22 **STEP 2: IDENTIFY INJURY MECHANISMS AND RISK FACTORS**

23

24 ***Mechanisms***

1 Once injury incidence and severity has been identified, S&C coaches may
2 begin to examine each injury and its accompanying mechanism. This will
3 involve biomechanical screening of movement patterns, which is indicative of
4 sporting situations that are characterized by increased injury risk (38). For
5 example, in sports where anterior cruciate ligament (ACL) injuries are
6 prevalent, activities involving rapid decelerations, such as changing direction
7 and landing from a jump, should be assessed (38, 67). Dysfunctional
8 movement patterns displayed during these activities involving positions of
9 heightened knee abduction will increase the strain on the ACL (41). If possible,
10 this should be verified with prospective cohort studies that show athletes who
11 exhibit these aberrant movement strategies increase their risk of injury (25).

12

13 Coaches should be aware that not all injuries have a definitive mechanism.
14 Overuse type pathologies, such as tendinopathy, are more likely to occur
15 through the application of an unaccustomed and excessive training load (16).
16 Many overuse injuries do have an associated movement pattern as it relates to
17 a specific sport. For example, patellar tendinopathy in a male volleyball player
18 is likely related to jumping activities (50), with landing strategies using greater
19 knee flexion increasing patella tendon loading (21). Therefore, mechanisms of
20 injury and risk factors should be considered alongside the demands of the sport
21 and a comprehensive monitoring program to more accurately determine the
22 athlete's injury risk at any given time point.

23

24 ***Risk Factors***

1 Injury risk factors can be characterized as either intrinsic or extrinsic (79).
2 Intrinsic risk factors relate to the individual in question: age, maturation, sex,
3 genetics, anthropometric measurements, health status, injury history, biomotor
4 qualities (e.g. maximal strength) and training background (8, 79). These factors
5 can then be used to individualize the injury prevention model to the athlete.
6 Extrinsic risk factors relate to environmental influences: equipment, playing
7 surface and weather (8, 79). Risk factors can be further divided into modifiable
8 (e.g. the athlete's maximal strength levels) and non-modifiable (e.g. the
9 athlete's gender) (7). Although non-modifiable risk factors are important for
10 coaches to recognize in order to estimate risk, this information is not useful in
11 the development of a test battery. However, identifying modifiable risk factors
12 is vital in order to more accurately assess the athletes risk of sustaining injuries
13 that are relevant to their sport (8).

14

15 Importantly, coaches should not view each risk factor as an isolated variable
16 that predisposes an athlete to injury. Instead, the complex interaction and
17 summation of each factor should be acknowledged, which results in an athlete
18 being more vulnerable to injury (8). For example, an athlete displaying a risk
19 factor during a screening does not necessarily indicate the athlete will get
20 injured. It is the exposure to the mechanism that will provide the stimulus, in
21 conjunction with other known risk factors that make injury a possible outcome
22 (8). As such, an athlete who presents with poor eccentric hamstring strength
23 possesses a functional deficit that may increase the risk of hamstring strain
24 (78). In some instances, this may not be a major concern for the S&C coach if
25 no other risk factors are present in the athlete's profile, or the athlete is not

1 exposed to high speed running as part of their training or competition. However,
2 if the athlete was also a male, with a previous history of hamstring strain and
3 competes in a sport where high speed running is routinely performed (55), weak
4 hamstring musculature may become a primary concern for the S&C coach.
5 Coaches must therefore perform a comprehensive risk factor analysis for each
6 individual, considering all variables that may predispose the athlete to injury.

7

8 **STEP 3: DESIGN AND IMPLEMENT A VALID AND RELIABLE TEST** 9 **BATTERY**

10 In designing a test battery to identify athletes who display a greater risk of injury,
11 coaches must select tests and procedures that are both valid and reliable (25).
12 Examining the available literature or conducting investigations in the field would
13 establish the reliability and validity of their testing protocols. There are currently
14 a range of field-based tests that may be employed to screen athletes for
15 modifiable risk factors such as hamstring strain (27), ACL injuries (66), shoulder
16 and elbow injuries (71), lateral ankle sprain (62), and low back pain (51). As
17 such, a number of options are available to the S&C coach that allows for the
18 collection of valid and reliable data for identifying functional deficits in
19 modifiable risk factors.

20

21 Once tests that assess relevant and modifiable risk factors have been selected
22 and performed, an athlete profile can be established. Following the completion
23 of the testing battery, the S&C coach can rank and prioritize deficiencies that
24 may be identified, which will provide an approximate estimate of the athlete's
25 injury risk. This can be accomplished by comparing the athlete's performance

1 with normative data that may be obtained within the literature on similar athletic
2 groups.

3

4 **STEP 4: PRIORITIZE AND IMPLEMENT INTERVENTIONS**

5 Research has shown the effects of targeted training programs on modifiable
6 risk factors, with concomitant reductions in the occurrence of injury (44)
7 including hamstring strains (4), ACL injuries (61), ankle sprains (54), shoulder
8 pathology (3), and low back pain (17). Furthermore, well-designed injury
9 prevention strategies have been shown to reduce the total number of injuries
10 in sports such as soccer (43), basketball (22), and distance running (81). At this
11 point, coaches should prioritize the goal of their interventions based on the
12 athlete's deficits as measured in the testing battery, as well as their estimated
13 overall risk as identified in step 1. Coaches should also ensure that
14 performance objectives are not neglected. From this perspective, a multi-
15 faceted approach should be adopted, discussed, and agreed with the athlete,
16 coaching, and medical staff.

17

18 **STEP 5: RETEST TO ASSESS THE EFFECTIVENESS OF THE TRAINING**

19 **INTERVENTION**

20 Following a period of training, coaches should retest the athlete in order to
21 assess the effectiveness of the intervention and reevaluate the athlete's injury
22 risk. This time-frame is dependent on the physical quality or skill being
23 developed, and realistic expectations as to when adaptations should have
24 occurred. For example, changes in ankle dorsiflexion range of motion are
25 possible following a single exposure to a mobilization intervention (37, 42);

1 however, improvements in fundamental movement patterns and muscle
2 architecture may take weeks to transpire (1, 10). Since changes in mobility
3 could be more immediate, retesting can take place directly after the application
4 of a single bout of mobilization. However, if motor control or structural changes
5 are desired, then testing sessions should be separated by a number of weeks
6 in order to observe appreciable changes.

7 Scheduling regular opportunities to retest should be seen as an evolving
8 process, with the injury prevention model being continually redeveloped as
9 updated research is published. Other factors may also lead to the evolution of
10 the injury prevention model, such as modifications to the sport itself that alter
11 the demands placed on the athlete (i.e. rule changes) and new experiences
12 that influence the coaches understanding of the potential injury risk. Likewise,
13 as the athlete's level of injury risk will change based on their physical
14 development, the model will require alterations. This may be driven by a
15 number of factors, such as an injury being sustained, growth and maturation or
16 advancing age that is placing them at a greater risk for certain types of injury
17 (i.e. hamstring strains (31)).

18

19 **DESIGNING THE INJURY PREVENTION MODEL**

20 To illustrate how the model and conceptual framework presented in this article
21 can be applied, a case study example has been included in figure 2. The
22 selected athlete is a 23-year-old male triple jumper, competing at international
23 level. Injury rates during the course of multiple seasons in track and field have
24 been shown to be a key determinant in an athlete's success (69). Track and
25 field events present athletes with a high injury risk across the course of the

1 season, with an injury occurrence rate between 3.1 to 169.8 injuries per 100
2 athletes depending on the event (18). For the men's triple jump event
3 specifically, Alonso et al. (2) recorded 125 injuries occur per 1000 athletes
4 within the competitive period.

5

6 Due to the nature of triple jump, acute injuries are a common occurrence when
7 compared to distance events (20). The majority of these injuries occur in the
8 lower extremity (2). In particular, thigh strains account for 22.8% of all injuries
9 in jumping events (23), with hamstring strains being the most common (19).
10 Ankle injuries are also widespread (22.7%), with sprains particularly prevalent
11 (23). Achilles tendinopathy has also been shown to be prevalent in athletes
12 competing in explosive events within track and field (18). Other sites of injury
13 for jumping events are the trunk (13.6%), knee (12.1%) and foot (10.6%) (23).

14

15 Regarding the severity of injuries, the greatest time loss following injuries
16 incurred from track and field events has been reported with hamstring strains
17 (2, 23). Other injuries in athletics that have been shown to lead to large periods
18 of time away from training and competitions (>4 weeks) include achilles tendon
19 injuries, ankle sprains, strains at the groin and lower leg, as well as lower leg
20 stress fractures (2). Based on injury incidence and severity presented here,
21 hamstring strains, ankle sprains and achilles tendinopathy should be prioritized
22 for the development of injury prevention strategies. As the available literature
23 indicates that hamstring strains are the most common (19) and display the
24 greatest severity (2, 19), a systems-based model will be applied herein to
25 illustrate its application.

1

2 Modifiable risk factors for hamstring strains include considerations centred on
3 flexibility, core stability, strength, and muscle architecture (55). Although local
4 flexibility of the hamstring musculature is poorly associated with injury risk (4),
5 reduced hip flexor (32) and ankle mobility (31) has been identified as potentially
6 problematic. This is due to poor hip extension and ankle dorsiflexion mobility
7 interfering with sprint mechanics by increasing hamstring length on the
8 contralateral extremity during the terminal swing phase leading to malalignment
9 of the pelvis (11), and disrupting ankle proprioception (31), respectively.
10 Likewise, the trunk musculature has also been shown to prevent excessive
11 lengthening of the hamstrings by controlling the sagittal plane orientation of the
12 pelvis during the terminal swing phase of sprinting (11). Deficits in core stability
13 therefore, has been suggested to increase the risk of hamstring injury during
14 sprinting (55).

15

16 As the hamstring musculature are required to contract while lengthening during
17 the terminal swing phase of sprinting (65, 77), eccentric strength tests are
18 recommended for screening. This is supported by evidence that low eccentric
19 hamstring strength has been shown to increase the risk of developing
20 hamstring injuries in Australian football players (64). Eccentric hamstring
21 strength may also provide valuable information regarding the architectural
22 make-up of the hamstrings, as athlete's with short fascicles in their biceps
23 femoris have been shown to possess poor eccentric strength (78). Reduced
24 fascicle length is hypothesized to increase hamstring strain risk, by cause an

1 overstretching of the hamstrings whilst they are contracting eccentrically during
2 the terminal swing phase (78).

3

4 As the hamstrings are both knee flexors and hip extensors, testing hamstring
5 strength with a focus only on knee flexion is potentially problematic as it ignores
6 their biarticular function (55). Therefore, it is suggested that hamstring strength
7 be tested with both knee flexion and hip extension based tests. This
8 recommendation is supported by Sugiura et al. (75), who highlighted hip
9 extensor strength as a risk factor in elite sprinters.

10

11 Figure 2 shows a sequential flow, whereby the injury risk is established and
12 followed by identification of mechanisms and modifiable risk factors. Relevant
13 tests have then been selected, which may be used to identify deficits in the
14 modifiable risk factors discussed. Each of the tests selected in figure 2 are
15 reliable enough to recognise a functional change and are associated with injury
16 (6, 12, 30, 47, 48, 63, 64, 75). Although some of these tests included may
17 require access to expensive equipment, coaches can either find more cost-
18 effective alternatives or develop their own tests as part of their own practice.
19 For example, if the S&C coach does not have access to an isokinetic
20 dynamometer, the single leg hamstring bridge may be an effective substitution
21 in order to measure hip extension strength (27). However, if novel assessments
22 are implemented and/or adapted to meet the needs of their environment, it is
23 recommended that their reliability should be examined with their own athletes.
24 This is to determine a 'true' change in performance can be accurately
25 quantified, which falls outside of the typical error associated with the test.

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INSERT FIGURE 2 HERE

Once deficits have been identified based on the athlete’s test scores, a training intervention can be designed and implemented. It is encouraged that coaches adopt evidenced-based training strategies. For example, data have shown hip extensor strength (13), eccentric hamstring strength (56), core stability (73) and flexibility (80) can all be improved following targeted training programs. Figure 2 provides some general suggestions for exercises that may be used to reduce the modifiable risk factors related to hamstring strains. This approach will allow S&C coaches to develop an individualized training process for each athlete seeking to reduce identified and modifiable injury risk factors, which in turn will maximize training transfer and effectiveness.

Table 1 illustrates how such exercises may be integrated into a training program for the triple jumper who presents with poor eccentric hamstring strength during testing. This program attempts to improve multiple qualities such as explosive and maximal strength of the leg extensors in order to enhance sports performance, while developing hamstring eccentric strength to reduce injury risk. In order to improve the transfer of training by developing the rate of force development of the posterior chain musculature during eccentric contractions, table 2 shows a training program that could be incorporated in the triple jumper’s weekly regime. For the interested reader, descriptions for how to perform many of these exercises are included in Sherry et al. (72).

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INSERT TABLE 1 AND 2 HERE

Furthermore, if myofascial or articular restrictions were identified during testing, Table 3 provides an example program that would develop that triple jumper’s mobility. This program could be prescribed as a standalone training program, or integrated into a thorough warm up prior to the performance of dynamic activities that ensure the athlete is prepared for the high intensity nature of training. In these examples, each program would be carefully distributed around the athlete’s technical training in order to achieve the goal of improving sports performance. Additionally, technical, nutritional, and psychological components would also be considered as part of a multifaceted high-performance approach to injury risk reduction that would include a thorough monitoring process.

INSERT TABLE 3 HERE

SUMMARY

While S&C coaches should always strive to improve sports performance, equal efforts must be made to reduce the risk of injury for each athlete. This article provides a step-by-step, systems-based model for designing injury prevention training programs. An evidence-based approach should form the foundation and the individual athlete should also be placed at the centre of the model. The current model aims to reduce modifiable risk factors through the incorporation of targeted training interventions, with the desired outcome of decreasing the athlete’s overall injury risk.

1 REFERENCES

- 2 1. Abe T, DeHoyos DV, Pollock ML and Garzarella L. Time course for
3 strength and muscle thickness changes following upper and lower body
4 resistance training in men and women. *Eur J Appl Physiol* 81:174 – 180,
5 2000.
- 6 2. Alonso JM, Edouard P, Fischetto G, Adams B, Depiesse F and Mountjoy
7 M. Determination of future prevention strategies in elite track and field:
8 analysis of Daegu 2011 IAAF Championships injuries and illnesses
9 surveillance. *Br J Sports Med* 46:505 – 514, 2012.
- 10 3. Andersson SH, Bahr R, Clarsen B and Myklebust G. Preventing overuse
11 shoulder injuries among throwing athletes: a cluster-randomised
12 controlled trial in 660 elite handball players. *Br J Sports Med*, 2016. [e-
13 pub ahead of print].
- 14 4. Arnason A, Andersen TE, Holme I, Engebretsen L and Bahr R.
15 Prevention of hamstring strains in elite soccer: an intervention study.
16 *Scand J Med Sci Sports* 18:40 – 48, 2008.
- 17 5. Bakken A, Targett S, Bere T, Eirale C, Farooq A, Tol JL, Whiteley R,
18 Khan KM and Bahr R. The functional movement test 9+ is a poor
19 screening test for lower extremity injuries in professional male football
20 players: a 2-year prospective cohort study. *Br J Sports Med*, 2017. [e-
21 pub ahead of print].
- 22 6. Bennell K, Talbot R, Wajswelner H, Techovanich W, Kelly DH and Hall
23 AJ. Intra-rater and inter-rater reliability of a weight-bearing lunge
24 measure of ankle dorsiflexion. *Aust J Physiother* 44:175 – 180, 1998.

- 1 7. Bahr R and Holme I. Risk factors for sports injuries--a methodological
2 approach. *Br J Sports Med* 37:384 – 392, 2003
- 3 8. Bahr R and Krosshaug T. Understanding injury mechanisms: a key
4 component of preventing injuries in sport. *Br J Sports Med* 39:324 – 329,
5 2005.
- 6 9. Bahr R. Why screening tests to predict injury do not work— and probably
7 never will...: a critical review. *Br J Sports Med* 50:776 – 780, 2016.
- 8 10. Bell DR, Oates DC, Clark MA and Padua DA. Two-and 3-dimensional
9 knee valgus are reduced after an exercise intervention in young adults
10 with demonstrable valgus during squatting. *J Athl Train* 48: 442 – 449,
11 2013.
- 12 11. Chumanov ES, Heiderscheit BC and Thelen DG. The effect of speed
13 and influence of individual muscles on hamstring mechanics during the
14 swing phase of sprinting. *J Biomech* 40:3555 – 3562, 2007.
- 15 12. Clapis PA, Davis SM and Davis RO. Reliability of inclinometer and
16 goniometric measurements of hip extension flexibility using the modified
17 Thomas test. *Physiother Theory Pract* 24:135 – 141, 2008.
- 18 13. Contreras B, Vigotsky AD, Schoenfeld BJ, Beardsley C, McMaster DT,
19 Reyneke JH and Cronin JB. Effects of a Six-Week Hip Thrust vs. Front
20 Squat Resistance Training Program on Performance in Adolescent
21 Males: A Randomized Controlled Trial. *J Strength Cond Res* 31:999 –
22 1008, 2017.
- 23 14. Cook G, Burton L and Hoogenboom B. Pre-participation screening: the
24 use of fundamental movements as an assessment of function—part 1. *N*
25 *Am J Sports Phys Ther* 1:62 – 72, 2006.

- 1 15. Cormery B, Marcil M and Bouvard M. Rule change incidence on
2 physiological characteristics of elite basketball players: a 10-year-period
3 investigation. *Br J Sports Med* 42:25 – 30, 2008.
- 4 16. Drew MK and Finch CF. The Relationship Between Training Load and
5 Injury, Illness and Soreness: A Systematic and Literature Review. *Sports*
6 *Med* 46:861 – 883, 2016.
- 7 17. Durall CJ, Udermann BE, Johansen DR, Gibson B, Reineke DM and
8 Reuteman P. The effects of preseason trunk muscle training on low-back
9 pain occurrence in women collegiate gymnasts. *J Strength Cond Res*
10 23:86 – 92, 2009.
- 11 18. Edouard P and Alonso JM. Epidemiology of track and field injuries.
12 *NSA* 28:85 – 92, 2013.
- 13 19. Edouard P, Branco P and Alonso JM. Muscle injury is the principal injury
14 type and hamstring muscle injury is the first injury diagnosis during top-
15 level international athletics championships between 2007 and 2015. *Br*
16 *J Sports Med* 50: 619 – 630, 2016.
- 17 20. Edouard P and Morel N. Prospective surveillance of injury in athletics.
18 A pilot study. *Sci Sports* 25:272 – 276, 2010.
- 19 21. Edwards S, Steele JR, McGhee DE, Beattie S, Purdam C and Cook JL.
20 Landing strategies of athletes with an asymptomatic patellar tendon
21 abnormality. *Med Sci Sports Exerc* 42:2072 – 2080, 2010.
- 22 22. Emery CA, Rose MS, McAllister JR and Meeuwisse WH. A prevention
23 strategy to reduce the incidence of injury in high school basketball: a
24 cluster randomized controlled trial. *Clin J Sport Med* 17:17 – 24, 2007.

- 1 23. Feddermann-Demont N, Junge A, Edouard P, Branco P and Alonso JM.
2 Injuries in 13 international Athletics championships between 2007–2012.
3 *Br J Sports Med* 48:513 – 522, 2014.
- 4 24. Finch C. An Overview of Some Definitional Issues for Sports Injury
5 Surveillance. *Sports Med* 24:157 – 163, 1997
- 6 25. Finch C. A new framework for research leading to sports injury
7 prevention. *J Sci Med Sport* 9:3 – 9, 2006.
- 8 26. Finch C and Cassell E. The public health impact of injury during sport
9 and active recreation. *J Sci Med Sport* 9:490 – 497, 2006.
- 10 27. Freckleton G, Cook J and Pizzari T. The predictive validity of a single leg
11 bridge test for hamstring injuries in Australian Rules Football Players. *Br*
12 *J Sports Med* 48:713 – 717, 2014.
- 13 28. Fuller CW, Ekstrand J, Junge A, Andersen TE, R Bahr, Dvorak J,
14 Hägglund M, McCrory P and Meeuwisse WH. Consensus statement on
15 injury definitions and data collection procedures in studies of football
16 (soccer) injuries. *Br J Sports Med* 40:193 – 201, 2006
- 17 29. Fuller CW, Molloy MG, Bagate C, Bahr R, Brooks JH, Donson H, Kemp
18 SP, McCrory P, McIntosh AS, Meeuwisse WH and Quarrie KL.
19 Consensus statement on injury definitions and data collection
20 procedures for studies of injuries in rugby union. *Br J Sports Med* 41:328
21 – 331, 2007.
- 22 30. Gabbe BJ, Bennell KL, Wajswelner H and Finch CF. Reliability of
23 common lower extremity musculoskeletal screening tests. *Phys Ther*
24 *Sport* 5:90 – 97, 2004.

- 1 31. Gabbe BJ, Finch CF, Bennell KL and Wajswelner H. Risk factors for
2 hamstring injuries in community level Australian football. *Br J Sports*
3 *Med* 39:106 – 110, 2005.
- 4 32. Gabbe BJ, Bennell KL and Finch CF. Why are older Australian football
5 players at greater risk of hamstring injury? *J Sci Med Sport* 9:327 – 33,
6 2006.
- 7 33. Garraway WM, Lee AJ, Hutton SJ, Russell EB and Macleod DA. Impact
8 of professionalism on injuries in rugby union. *Br J Sports Med* 34: 348 –
9 351, 2000.
- 10 34. Gessel LM, Fields SK, Collins CL, Dick RW and Comstock RD.
11 Concussions among United States high school and collegiate athletes.
12 *J Athl Train* 42:495-503. 2007.
- 13 35. Gissane C, Jennings D, Kerr K and White J. Injury rates in rugby league
14 football: impact of change in playing season. *Am J Sports Med* 31:954 -
15 958, 2003.
- 16 36. Gomez E, DeLee JC and Farney WC. Incidence of injury in Texas girls'
17 high school basketball. *Am J Sports Med* 24:684 – 687, 1996.
- 18 37. Halperin I, Aboodarda SJ, Button DC, Andersen LL and Behm DG.
19 Roller massager improves range of motion of plantar flexor muscles
20 without subsequent decreases in force parameters. *Int J Sports Phys*
21 *Ther* 9:92 – 102, 2014.
- 22 38. Havens KL and Sigward SM. Cutting mechanics: relation to performance
23 and anterior cruciate ligament injury risk. *Med Sci Sports Exerc* 47:818
24 – 824, 2015.

- 1 39. Hewett TE, Stroupe AL, Nance TA and Noyes FR. Plyometric training in
2 female athletes. Decreased impact forces and increased hamstring
3 torques. *Am J Sports Med* 24:765 – 773, 1996.
- 4 40. Hewett TE, Myer GD, Ford KR, Heidt RS, Colosimo AJ, McLean SG,
5 Van den Bogert AJ, Paterno MV and Succop P. Biomechanical
6 measures of neuromuscular control and valgus loading of the knee
7 predict anterior cruciate ligament injury risk in female athletes a
8 prospective study. *Am J Sports Med* 33:492 – 501, 2005.
- 9 41. Hewett TE, Ford KR and Myer GD. Anterior cruciate ligament injuries in
10 female athletes: Part 2, a meta-analysis of neuromuscular interventions
11 aimed at injury prevention. *Am J Sports Med* 34:490 – 498, 2006.
- 12 42. Howe LP. The acute effects of ankle mobilisations on lower extremity
13 joint kinematics. *J Bodyw Mov Ther.* 2016. [In Press].
- 14 43. Junge A, Rösch D, Peterson L, Graf-Baumann T and Dvorak J.
15 Prevention of soccer injuries: a prospective intervention study in youth
16 amateur players. *Am J Sports Med* 30:652 – 659, 2002.
- 17 44. Junge A, Engebretsen L, Alonso JM, Renström P, Mountjoy M, Aubry M
18 and Dvorak J. Injury surveillance in multi-sport events: the International
19 Olympic Committee approach. *Br J Sports Med* 42:413 – 421, 2008
- 20 45. Kiesel K, Plisky PJ and Voight ML. Can serious injury in professional
21 football be predicted by a preseason functional movement screen? *N*
22 *Am J Sports Phys Ther* 2:147 - 158, 2007.
- 23 46. Klügl M, Shrier I, McBain K, Shultz R, Meeuwisse WH and Garza D,
24 Matheson GO. The prevention of sport injury: an analysis of 12,000
25 published manuscripts. *Clin J Sport Med* 20:407 – 412, 2010.

- 1 47. Konor MM, Morton S and Eckerson JM. Reliability of three measures of
2 ankle dorsiflexion range of motion. *Int J Sports Phys Ther* 7:279 – 287,
3 2012.
- 4 48. Krause DA, Youdas JW, Hollman JH and Smith J. Abdominal muscle
5 performance as measured by the double leg-lowering test. *Arch Phys*
6 *Med Rehabil* 86:1345 – 1348, 2005.
- 7 49. Kröll J, Spörri J, Steenstrup SE, Schwameder H, Müller E and Bahr R.
8 How can we prove that a preventive measure in elite sport is effective
9 when the prevalence of the injury (eg, ACL tear in alpine ski racing) is
10 low? A case for surrogate outcomes. *Br J Sports Med*, 2016. [e-pub
11 ahead of print].
- 12 50. Laforgia R, Capocasale N, Saracinon N and Solarino eM. A clinical and
13 ultrasonographic study of jumper's knee and the achilles tendon in
14 volleyball players. *J Sports Traumatol Relat Res* 14:127 – 138, 1992.
- 15 51. Luoto S, Heliövaara M, Hurri H and Alaranta H. Static back endurance
16 and the risk of low-back pain. *Clin Biomech* 10:323 – 324, 1995.
- 17 52. McCall A, Carling C, Nedelec M, Davison M, Le Gall F, Berthoin S and
18 Dupont G. Risk factors, testing and preventative strategies for non-
19 contact injuries in professional football: current perceptions and
20 practices of 44 teams from various premier leagues. *Br J Sports Med*
21 48:1352 – 1357, 2014.
- 22 53. McCunn R, Aus der Fünten K., Fullagar HH, McKeown I and Meyer T.
23 Reliability and Association with Injury of Movement Screens: A Critical
24 Review. *Sports Med* 46:763 – 781, 2016.

- 1 54. McGuine TA and Keene JS. The effect of a balance training program on
2 the risk of ankle sprains in high school athletes. *Am J Sports Med*
3 34:1103 – 1111, 2006.
- 4 55. Mendiguchia J, Alentorn-Geli E and Brughelli M. Hamstring strain
5 injuries: are we heading in the right direction? *Br J Sports Med* 46:81 –
6 85, 2012.
- 7 56. Mjølshes R, Arnason A, Raastad T and Bahr R. A 10-week randomized
8 trial comparing eccentric vs. concentric hamstring strength training in
9 well-trained soccer players. *Scand J Med Sci Sports* 14:311 – 317, 2004.
- 10 57. Moran RW, Schneiders AG, Mason J and Sullivan SJ. 2017. Do
11 Functional Movement Screen (FMS) composite scores predict
12 subsequent injury? A systematic review with meta-analysis. *Br J Sports*
13 *Med*, 2016. [e-pub ahead of print].
- 14 58. Montgomery RD. Healing of muscle, ligaments, and tendons. *Semin Vet*
15 *Med Surg* 4:304 – 311, 1989.
- 16 59. Myer GD, Ford KR, Palumbo JP and Hewett TE. Neuromuscular training
17 improves performance and lower-extremity biomechanics in female
18 athletes. *J Strength Cond Res* 19:51 – 60, 2005.
- 19 60. Myer GD, Ford KR, McLean SG and Hewett TE. The effects of
20 plyometric versus dynamic stabilization and balance training on lower
21 extremity biomechanics. *Am J Sports Med* 34:445 – 455, 2006.
- 22 61. Myklebust G, Engebretsen L, Brækken IH, Skjølberg A, Olsen OE and
23 Bahr R. Prevention of anterior cruciate ligament injuries in female team
24 handball players: a prospective intervention study over three seasons.
25 *Clin J Sport Med* 13:71 – 78, 2003.

- 1 62. Olmsted LC, Carcia CR, Hertel J and Shultz SJ. Efficacy of the star
2 excursion balance tests in detecting reach deficits in subjects with
3 chronic ankle instability. *J Athl Train* 37:501 – 506, 2002.
- 4 63. Opar DA, Piatkowski T, Williams MD and Shield AJ. A novel device using
5 the Nordic hamstring exercise to assess eccentric knee flexor strength:
6 a reliability and retrospective injury study. *J Orthop Sports Phys Ther*
7 43:636 – 640, 2013.
- 8 64. Opar DA, Williams M, Timmins R, Hickey J, Duhig S and Shield A.
9 Eccentric hamstring strength and hamstring injury risk in Australian
10 footballers. *Med Sci Sports Exerc*, 46:857 – 865, 2014.
- 11 65. Orchard J. Biomechanics of muscle strain injury. *Sports Med* 30:92 – 98,
12 2002.
- 13 66. Padua DA, Marshall SW, Boling MC, Thigpen CA, Garrett Jr WE and
14 Beutler, AI. The Landing Error Scoring System (LESS) is a valid and
15 reliable clinical assessment tool of jump-landing biomechanics: the
16 JUMP-ACL study. *Am J Sports Med* 37:1996 – 200, 2009.
- 17 67. Phillips N and van Deursen RW. Landing stability in anterior cruciate
18 ligament deficient versus healthy individuals: a motor control approach.
19 *Phys Ther Sport* 9:193 – 201, 2008.
- 20 68. Plisky PJ, Rauh MJ, Kaminski TW and Underwood FB. Star Excursion
21 Balance Test as a predictor of lower extremity injury in high school
22 basketball players. *J Orthop Sports Phys Ther* 36:911 – 919, 2006.
- 23 69. Raysmith BP and Drew MK. Performance success or failure is
24 influenced by weeks lost to injury and illness in elite Australian track

- 1 and field athletes: A 5-year prospective study. *J Sci Med Sport* 19:778
2 – 783, 2016.
- 3 70. Read PJ, Oliver JL, De Ste Croix MB, Myer GD and Lloyd RS.
4 Neuromuscular Risk Factors for Knee and Ankle Ligament Injuries in
5 Male Youth Soccer Players. *Sports Med* 46:1059 – 1066, 2016
- 6 71. Shanley E, Rauh MJ, Michener LA, Ellenbecker TS, Garrison JC and
7 Thigpen CA. Shoulder range of motion measures as risk factors for
8 shoulder and elbow injuries in high school softball and baseball players.
9 *Am J Sports Med* 39:1997 – 2006, 2011.
- 10 72. Sherry MA, Best TM, Silder A, Thelen DG and Heiderscheit BC.
11 Hamstring strains: basic science and clinical research applications for
12 preventing the recurrent injury. *Strength Cond J* 33:56 – 71, 2013.
- 13 73. Stanton R, Reaburn PR and Humphries B. The effect of short-term Swiss
14 ball training on core stability and running economy. *J Strength Cond Res*
15 18:522 – 528, 2004.
- 16 74. Stevenson MR, Hamer P, Finch CF, Elliot B and Kresnow M. Sport, age,
17 and sex specific incidence of sports injuries in Western Australia. *Br J*
18 *Sports Med* 34:188 – 194, 2000.
- 19 75. Sugiura Y, Saito T, Sakuraba K, Sakuma K and Suzuki E. Strength
20 deficits identified with concentric action of the hip extensors and
21 eccentric action of the hamstrings predispose to hamstring injury in elite
22 sprinters. *J Orthop Sports Phys Ther* 38:457 – 464, 2008.
- 23 76. Sundaram A, Bokor DJ and Davidson AS. Rugby Union on-field position
24 and its relationship to shoulder injury leading to anterior reconstruction
25 for instability. *J Sci Med Sport* 14:111 – 114, 2011.

- 1 77. Thelen DG, Chumanov ES, Best TM, Swanson SC and Heiderscheit BC.
2 Simulation of biceps femoris musculotendon mechanics during the
3 swing phase of sprinting. *Med Sci Sports Exerc* 37:1931 – 1938, 2005.
- 4 78. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C and Opar
5 DA. Short biceps femoris fascicles and eccentric knee flexor weakness
6 increase the risk of hamstring injury in elite football (soccer): a
7 prospective cohort study. *Br J Sports Med* 50:1524 – 1535, 2016.
- 8 79. van Mechelen W, Hlobil H and Kemper HCG. Incidence, severity,
9 aetiology and prevention of sports injuries. A review of concepts. *Sports*
10 *Med* 14:82 – 99, 1992.
- 11 80. Winters MV, Blake CG, Trost JS, Marcello-Brinker TB, Lowe L, Garber
12 MB and Wainner RS. Passive versus active stretching of hip flexor
13 muscles in subjects with limited hip extension: a randomized clinical trial.
14 *Phys Therapy* 84:800 – 807, 2004.
- 15 81. Yeung EW and Yeung SS. A systematic review of interventions to
16 prevent lower limb soft tissue running injuries. *Br J Sports Med* 35:383 –
17 389, 2001.

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1 **Figure 1.** Step process for developing injury prevention training strategies to
2 reduce injury risk.

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4 **Figure 2.** Injury prevention process specific to reducing hamstring strain risk
5 for an international male triple jumper.

6

7 **Table 1.** Example training program aimed at improving sports performance and
8 reducing modifiable risk factors that are associated with hamstring strains.

9

10 **Table 2.** Example program aimed at improving coordination and rate of force
11 development of the hamstring musculature.

12

13 **Table 3.** Example mobility program aimed at reducing modifiable risk factors
14 that are associated with hamstring strains.

15