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Clinical Commentary/Current Concept Review

Noncontact Knee Ligament Injury Prevention Screening in Netball: A Clinical Commentary with Clinical Practice Suggestions for Community-Level Players

Nicholas C Clark, PhD, MCSP, MMACP, CSCS[1 a]

[1] School of Sport, Rehabilitation, and Exercise Sciences, University of Essex

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Netball is a predominantly female team court-sport which is played worldwide. Netball is becoming more popular in the United States following its countrywide introduction to schools and community centers. A unique characteristic of netball is the footwork rule which restricts players to a one-step landing after catching the ball. Most netball landings are single-leg landings resulting in high vertical ground reaction forces and high skeletal tissue forces. Thus, high-risk landing events that have the biomechanical potential for injury occur frequently. Noncontact knee ligament injuries are common following a knee abduction collapse when landing. Because the consequences of noncontact knee ligament injury are profound, strategies are needed to mitigate the burden of such injury for players, teams, and society.

The purpose of this clinical commentary is to demonstrate how theoretical principles, different types of research, and different levels of evidence underpin a rational clinical reasoning process for developing noncontact knee ligament injury prevention screening procedures in netball. The theoretical principles that are discussed in this commentary include injury control, the sequence of prevention, principles of screening in injury prevention, the multifactorial model of injury etiology, complex systems theory, and systems science. The different types of research that are reviewed include descriptive and analytic-observational studies. The different levels of evidence that are discussed include prospective studies, cross-sectional studies, and clinicians' own kinesiological modelling. Subsequently, an integrated approach to the evidence-informed development of noncontact knee ligament injury prevention screening procedures is presented. Clinical practice suggestions include a selection of evidence-informed screening tests that are quickly and easily implemented with netball players in local communities. The need for repeated screening at strategic timepoints across a season/year is explained. Sports physical therapists will find this commentary useful as an example for how to undertake clinical reasoning processes that justify the content of screening procedures contributing to noncontact knee ligament injury prevention in community-level netball.

Level of Evidence

5

BACKGROUND AND PURPOSE

Netball is a predominantly female team sport with millions of players across 117 countries.[1] Netball evolved from women's basketball in the 1890s, was first played in England in 1895, and later became popular across the British Commonwealth.[2] In England in 2017, there were 180,200 adult netball players[3] which increased to 321,200 players by

a **Corresponding author:**
Nicholas C. Clark, PhD, MCSP, MMACP, CSCS.
Lecturer (Education and Research) - Physiotherapy.
School of Sport, Rehabilitation, and Exercise Sciences.
University of Essex.
Wivenhoe Park, Colchester, Essex, CO4 3SQ. United Kingdom.
n.clark@essex.ac.uk

Table 1: Definitions of contact, indirect contact, and noncontact knee injury*

Classification and Definition	Example
Contact injury	
Following contact with the player's knee from an opponent or some external object	When a direct blow to the player's knee occurs from an opponent who collides with the player following a slip/trip/fall.
Indirect contact injury	
Following contact with another part of the player's body (e.g. trunk) from an opponent or some external object	When the player and an opponent are side-by-side and jumping upwards to contest for the ball and the opponent 'bumps' the player's shoulder
Noncontact injury	
Following an athletic maneuver without any contact from an opponent or some external object	When a player decelerates suddenly when landing from a leap or cutting to change direction

*Modified from references: 27, 66, 74

2019.[4] In 2018, there were 486,618 registered netball players in Australia[5] and 145,000 registered players in New Zealand.[6] In the United States (US), netball is a relatively new sport which gained popularity in the 1980s.[7] Recently, Miami hosted the World University Netball Championships in 2016[8] and the US Open Netball Championships attracted over 100,000 viewers in 2017.[7] Now, Netball America has members in 33 states[7] and a new high-performance development pathway exists following the success of the US University Netball Team.[9] Community-level netball participation in America is expected to grow following netball's countrywide introduction to schools and community centers and tournaments at venues such as Madison Square Garden.[7] With increased sport participation comes an increase in injury frequency.[10–12]12 Because of growing participation in netball in America, it is prudent for sports physical therapists to become familiar with the nature of the game and to consider primary injury control interventions with community-level players.

Netball is a court-based team game played over 15-minute quarters.[13] Netball is played on indoor and outdoor courts and requires rapid acceleration, deceleration, and change-of-direction running along with jumping, leaping, and ball throwing/catching when attempting to score a goal in the opponent's territory.[13–15] A unique characteristic of netball is the 'footwork rule' which restricts players to a one-step landing after catching the ball.[13] In other words, after touching down with one foot, players can only take one more step with the other foot to decelerate the body; after this, players may pivot on the touchdown foot before passing the ball to a teammate.[13] The requirement to obey the footwork rule and stop suddenly with one step results in frequent single-leg landing (SLL) with vertical ground reaction force (VGRF) ranging from 3.5[16] to 5.7[17] times bodyweight (BW). The VGRF is of interest because it contributes to shear, compression, and rotation forces experienced by the lower-limb joints[18,19] and because SLL and double-leg landing (DLL) are involved in 27.1-73.8% of injury events.[20–23]

Knee injuries account for substantial proportions of netball lower-limb injuries.[21,22,24,25] Across studies, the majority of netball knee injuries are of a noncontact nature[20,21,23,26,27] (Table 1). Trauma accounts for 26% of knee injuries referred to the emergency room[26] and approximately one-third of netball-related hospitalizations.[28] Anterior cruciate ligament (ACL) and meniscus tears occur in netball with a respective frequency of 17.2-22.4% and 4.5-32.7%.[24,26] When comparing netball to basketball, female ACL sprains and meniscus tears demonstrate higher proportions in netball (17.2%, 4.5%) than basketball (11.1%, 4.1%).[24] Considering ACL-reconstruction (ACLR) incidence between sports, a higher rate of ACLR is also evident in netball (188/100,000 participants) than basketball (109/ 100,000 participants).[29] Anterior cruciate ligament and meniscus injuries result in profound consequences such as physical disability,[28,30] substantial healthcare costs,[29–32] disrupted academic studies,[33,34] premature retirement from netball,[35] post-trauma osteoarthritis,[36,37] and depression.[38,39] Risk of suicide can also exist after sports injuries.[40,41] Because of such consequences, interventions are needed to mitigate the burden of knee ligament injury for players, teams, and society, and prolong players' safe netball participation across the lifespan.

The purpose of this clinical commentary is to demonstrate how theoretical principles, different types of research, and different levels of evidence underpin a rational clinical reasoning process for developing noncontact knee ligament injury prevention screening procedures in netball. An understanding of theoretical principles that support clinical practice is critical for designing evaluation and treatment interventions, deploying such interventions in the correct clinical context at the right time, and setting clinicians' and athletes' expectations appropriately relative to desired outcomes. This commentary will discuss how theoretical principles and different levels of evidence[42] can be translated to and applied within sports physical therapy practice for primary prevention screening for noncontact knee ligament injury in community-level netball. Several paradigms will illustrate the implications of selected theoretical principles for such practice, including stages of injury control,[43–45] sequence of prevention,[46–49] principles of screening in injury prevention,[50] multifactorial model of injury etiology,[51] complex systems theory,[52] and systems science.[53,54] This commentary is original because no similar work exists in the netball literature. Sports physical therapists will find this commentary useful as an example for how to undertake clinical reasoning processes that justify the content of screening procedures contributing to noncontact knee ligament injury prevention in community-level netball.

DESCRIPTION OF THEORETICAL PRINCIPLES

STAGES OF INJURY CONTROL

Injury control refers to preventing or reducing the severity of injury[43,45] and includes prevention, acute care, and rehabilitation phases of healthcare.[44,45] Injury prevention refers to primary prevention of injury; that is, prevention of first-time injury to a bodypart.[46,55] Injury prevention includes all countermeasures to eliminate *or* minimize the occurrence of injury.[43,46] Injury prevention, therefore, does not refer to literal prevention of *all* injury cases but the prevention of as many cases as possible.[43,46,55] Injury prevention seeks to reduce the *probability* of sustaining an injury rather than to achieve *certainty* that all cases can be averted.[44,46,56] For the sports physical therapist, practice which recognizes prevention of all noncontact knee ligament injuries across time is not possible relative to probability theory (the likelihood that one event will occur given all possible outcomes)[57,58] facilitates action from a place of scientifically-informed realistic intention and good conscience.[59]

SEQUENCE OF PREVENTION

Injury prevention includes evaluation and intervention procedures that combine to decrease the probability for and incidence of injury.[44,46] The "sequence of prevention" refers to a process intended to culminate in such outcomes.[49] The process includes four steps: 1. establish the incidence and severity of injury (epidemiology); 2. establish the factors contributing to and mechanisms of injury; 3. introduce prevention countermeasures (interventions); 4. assess intervention effectiveness by repeating step one.[49] This process has been elaborated upon by other researchers,[48] and correspond to long-standing public health disease prevention models.[44,46] This commentary addressed step one (above) by establishing the frequency of ACL injury and ACLR in netball. This commentary addresses step two (below) by considering noncontact knee ligament injury mechanisms (i.e. mechanics of injury) and the factors associated with them (i.e. etiology of injury). The implication is that when a thorough undertaking of step two has occurred the sports physical therapist can consider appropriate evaluation (screening) procedures that, in turn, inform the content of step three and its interventions.[44,46]

PRINCIPLES OF SCREENING IN INJURY PREVENTION

In medicine, screening is a process to identify the presence or absence of disease.[60] In sports medicine, the analogy is screening as a process to identify the presence or absence of injury.[50] In injury prevention, the intent is to intervene *before* an injury occurs rather than diagnose an *existing* injury.[50] Screening in injury prevention, therefore, is a process to identify characteristics (factors) that increase athletes' probability of sustaining an injury.[50] These characteristics are then termed 'risk factors'.[51,58] Risk factors are intrinsic (inside) and extrinsic (outside) to the player.[46,49,61] In netball, examples of intrinsic and extrinsic risk factors for noncontact knee ligament injury appear in Table 2. Risk factors are also modifiable and nonmodifiable (Table 2).[62] Modifiable risk factors (e.g. muscle strength) and nonmodifiable risk factors (e.g. age) can and cannot be altered with conservative interventions, respectively.[62] For the sports physical therapist, the implication of intrinsic/extrinsic and modifiable/nonmodifiable risk factors is that the type and number of risk factors included in a screening test battery requires careful consideration. This consideration ensures the most clinically-amenable risk factors are evaluated and screening procedures are performed time-efficiently.

MULTIFACTORIAL MODEL OF INJURY ETIOLOGY

Because the probability of sustaining an injury is influenced by a combination of intrinsic and extrinsic risk factors, the etiology (cause) of injury is multifactorial.[51,63] A combination of intrinsic ('predisposing') risk factors can sensitize a player to injury,[51,64] while a combination of extrinsic ('necessary') risk factors must be present for an injury to occur.[51,64] Therefore, the temporal relationship of risk factors is critical: some combination of intrinsic and extrinsic risk factors must exist *before* an injury event can happen (Figure 1).[51,64] When a combination of factors produces an injury event within a specific situation, the factors are termed a "sufficient cause".[51,63,64] Screening to determine the presence/absence of intrinsic risk factors, therefore, relates to identifying an athlete predisposed to injury ("predisposed athlete")[51,65,66] (Figure 1). When a predisposed athlete enters a situation containing extrinsic risk factors, the athlete becomes susceptible to injury ("susceptible athlete")[51,65,66] (Figure 1). When the intrinsic and extrinsic risk factors interact within a specific situation as a sufficient cause, an injury event manifests (Figure 1).[50,63,65,67] Therefore, for the sports physical therapist in netball, injury prevention screening is about identifying the predisposed player possessing intrinsic risk factors for noncontact knee ligament injury *before* entering a competitive environment (e.g. outdoor court), context (e.g. league match), or situation (e.g. offensive play).

COMPLEX SYSTEMS THEORY

A complex system is a collection of interacting components where the behavior of the whole system cannot be predicted with 100% accuracy from the behavior (status) of one component alone.[52,68,69] Given the human body is composed

Table 2: Examples of intrinsic and extrinsic risk factors for noncontact knee ligament injury in netball

Intrinsic Risk Ractors		Extrinsic Risk Factors	
Modifiable	*Nonmodifiable*	*Modifiable*	*Nonmodifiable*
Joint stiffness	Age	Indoor climate	Outdoor weather
Muscle strength	Sex	Playing surface	
Balance	Femoral intercondylar		
	notch width		
Neurocognitive	General joint		
performance	hypermobility		
Landing movement			
pattern			

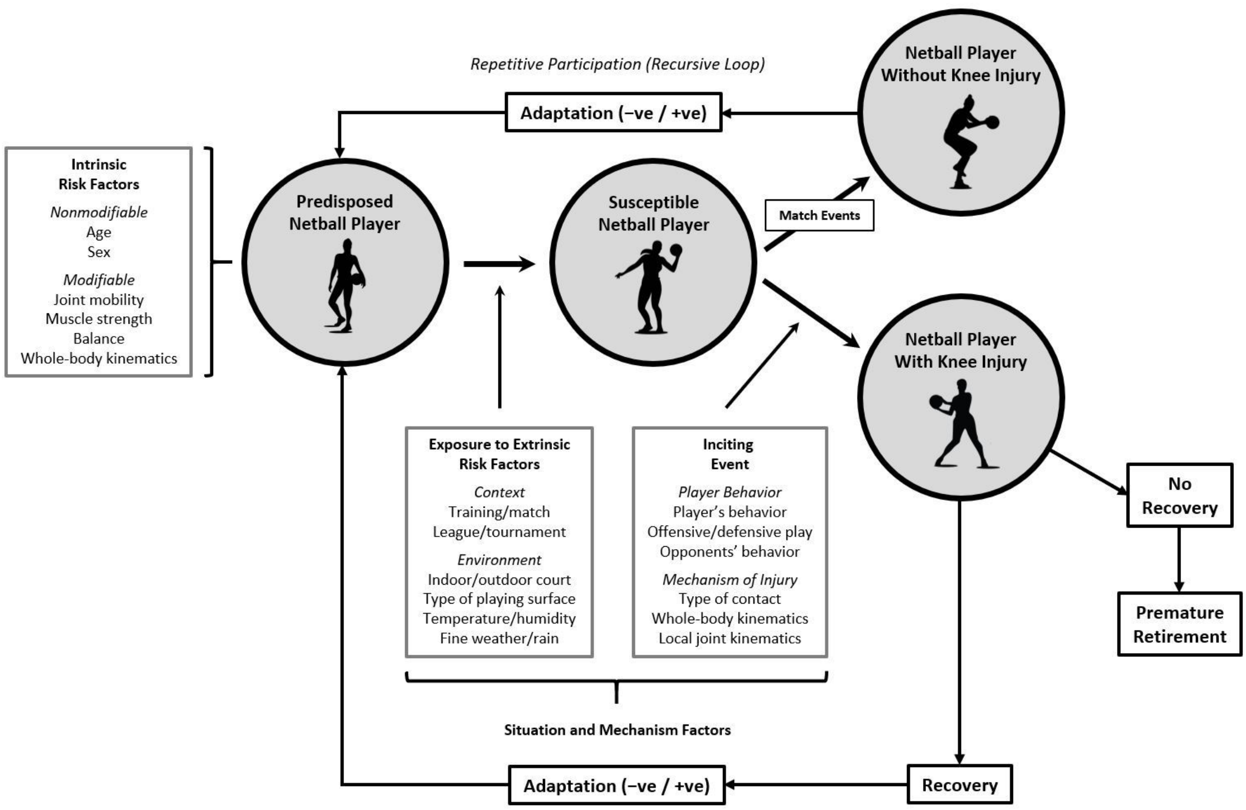

Figure 1: Example recursive and multifactorial model of netball noncontact knee ligament injury etiology (Modified from references 51, 65-67)

of multiple systems (e.g. skeletal, muscular, nervous, etc.) where each system itself is composed of many parts, an athlete is, by definition, a complex system. A netball player's physiological (e.g. hydration levels, glycogen levels), physical (e.g. joint range-of-motion [ROM], muscle strength), and psychoemotional (e.g. stress, anxiety) status can change between matches, across the season, and across the off-season. A netball match's environment (e.g. outdoor vs.

indoor court) and context (e.g. annual league vs. weekend tournament) can alter from week-to-week. A netball player, therefore, competes within repeating (recursive) loops that span different units of time (e.g. match-to-match, season duration, off-season duration) where sets of risk factors can alter/adapt within and between units of time (Figure 1).[52,65] As such, multiple interacting risk factors form a complex "web of determinants" that shift the probability for injury up-and-down across time.[46,51,52,65,70] Given probability theory[57,58] and complex systems theory,[52,68–71] injury prevention screening is not contextual to *predicting* which specific player *will* get injured.[46,50] Injury prevention screening is instead contextual to identifying athletes with combinations (patterns) of risk factors that contribute to an increased probability for injury.[46,50] For the sports physical therapist, noncontact knee ligament injury prevention screening should aim to identify patterns of modifiable intrinsic risk factors (multifactorial 'risk profile'[52]) for one point-in-time. Screening is then repeated (serial screening) at appropriate timepoints across a season/year to reveal changes in a player's risk profile.[50]

SYSTEMS SCIENCE

Systems science refers to viewing a clinical problem-space as a system of interconnected, interacting components.[54,69,72] Systems science is a foundation for complex systems theory which, in turn, informs the design of complex clinical interventions.[73] A fundamental principle in systems science is the use of different types of research to develop clinical interventions.[54,69,72] In sports physical therapy, an example of a systems science approach to problem-solving is using different levels of evidence[42] (e.g. prospective research + cross-sectional research + individual opinion) in clinical reasoning processes. The integration of different types of research in a clinician's reasoning yields a richer understanding of a problem-space than when one kind of research is considered alone.[54,69,72] In this commentary, descriptive[58] (injury mechanisms) and analytic-observational[58] (cross-sectional, prospective) *in vivo* and *in vitro* human research studies are combined with basic kinesiological modelling to develop rational screening procedures contributing to noncontact knee ligament injury prevention in netball (Figure 2).

MECHANISM OF NONCONTACT KNEE LIGAMENT INJURY IN NETBALL

Knowledge of the mechanism of knee injury gives insight into a player's movement patterns at the instant-of-injury and the anatomical structures that are damaged. This knowledge contributes to step two of the sequence of prevention.[49] Descriptive studies report small proportions (4.5-18.7%) of netball injuries occur during sudden stops when running or cutting to change direction[21,25,27] with larger proportions (27.0-73.8%) occurring during landings.[20,21,23,25] Other descriptive work reports 38-50% of knee injuries,[25,26] 81.3% of ACL injuries,[27] and 100% of medial collateral ligament (MCL) injuries[25] occurred during landings. Specifically, of all landing ACL injuries, 53.8% occurred during SLLs and 46.2% occurred during DLLs.[27] Of all netball knee injuries, 24-29% followed contact with another player,[20,21,23] although such injuries were not subdivided into direct or indirect contact[74] (Table 1). One group performed detailed video analyses of netball ACL injuries and reported 50% followed indirect contact when airborne and contesting for the ball and 50% were noncontact when landing from receiving a mid-air pass.[27] Together, descriptive studies indicate the majority of netball knee injuries are noncontact.[20,21,23,25–27]

Concerning whole-body kinematics when landing, support-leg trunk ipsilateral lateral flexion coupled with knee abduction was observed in 83.3% of netball noncontact ACL injuries.[27] Frontal plane trunk motion relative to the knee is of interest because it can increase support-leg knee abduction forces.[75] Because whole-body kinematics occur over a support-leg (i.e. weight-bearing leg), knee abduction motions are coupled with hip adduction and internal rotation (IR), knee flexion and IR, and foot pronation.[27,76] The coupled trunk, hip, knee, and foot motions are termed a "valgus collapse"[76] where knee valgus is synonymous with knee abduction. Concerning local knee joint kinematics, human cadaver (*in vitro*) research is useful for gaining insight into how joint kinematics influence ligament loads. Anterior tibial displacement (ATD), abduction, and IR generate ACL load/stress and elongation/strain.[77–79] When such uniplanar motions are superimposed on each other to elicit a combined motion pattern of ATD + abduction + IR, ACL stress and strain increase exponentially.[77–79] Because of the abduction component, the pattern also generates MCL stress and strain.[79,80] Knee multiplanar combined motions such as those just described have been observed in 83.3% of netball noncontact knee injuries.[27] When the mechanism of noncontact knee ligament injury is understood, the sports physical therapist can devise injury prevention screening procedures that identify which players may be predisposed to landings with kinematic patterns linked to injury-inducing events.

BIOMECHANICS OF NETBALL LANDINGS AND HIGH-RISK EVENTS

After knowledge of the mechanism of noncontact knee ligament injury is gained from descriptive studies, cross-sectional laboratory-based studies are employed to acquire a deeper understanding of the biomechanics of athletic tasks linked to the injury-inducing events (Figure 2). Specifically, laboratory-based studies are useful for developing a detailed kinetic and kinematic profile of athletic tasks associated with the mechanism of noncontact knee ligament injury. This profile then facilitates a deeper understanding of why such athletic tasks are 'high-risk' events that contain the potential for injury and further contributes to step two of the sequence of prevention.[49] Because the majority of knee injuries occur during landings,[25–27] focus will now be on the kinetics and kinematics of netball landings as high-risk events using variables popular in the netball literature.

The peak VGRF is of interest because it represents a foot-ground impact force that contributes to compression/shear/rotation forces experienced by the knee joint.[18,19] For DLLs after catching a pass, VGRFs were 5.7BW.[16] For SLLs with and without catching a pass, VGRFs were 3.5-5.7BW[16,17]

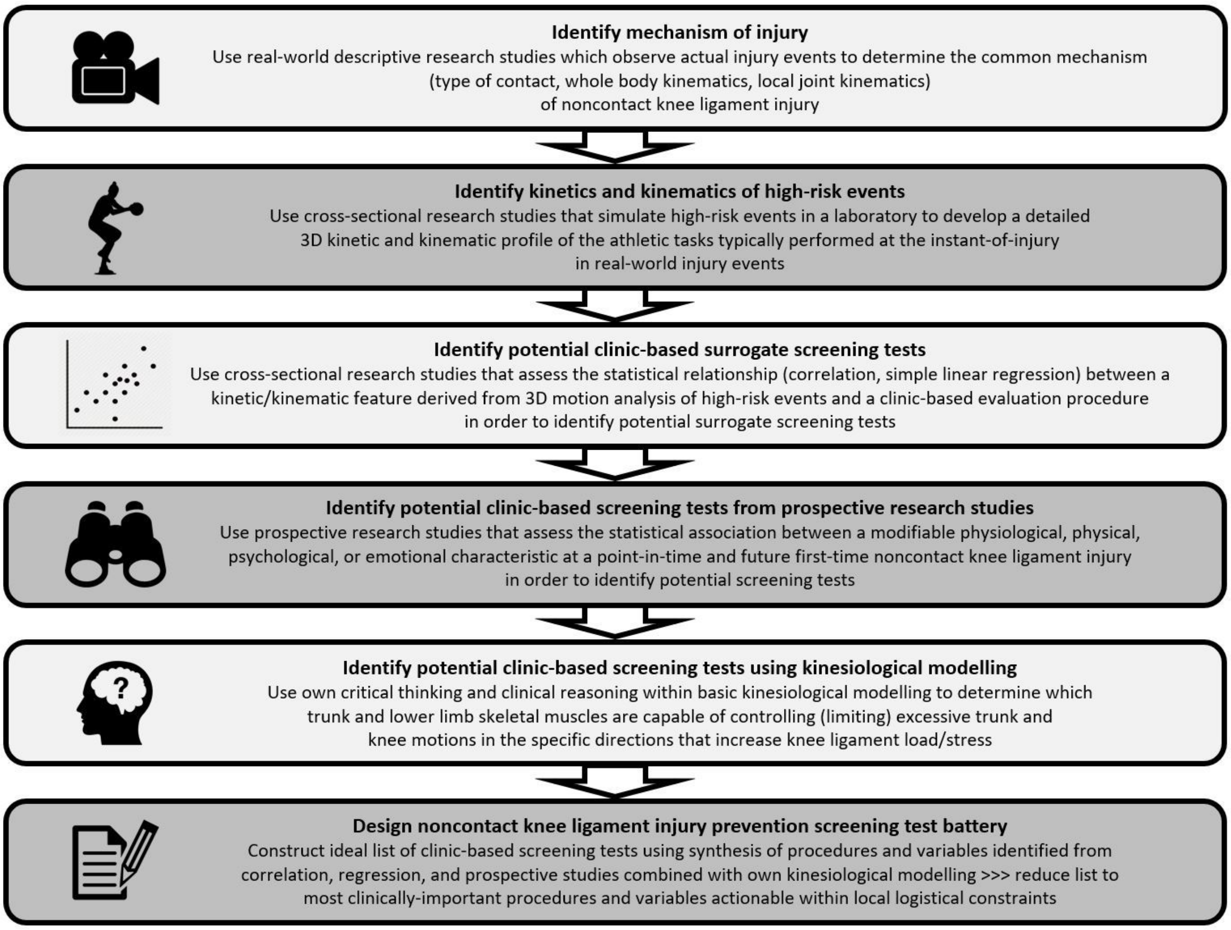

Figure 2: Example steps, types of research, and levels of evidence used to devise clinically-reasoned, netball-specific, noncontact knee ligament injury prevention screening tests

and 3.4BW,[81] respectively. The time-to-peak VGRF (TTPVGRF) is of interest because short TTPVGRFs correspond to higher rate-of-loading of skeletal tissues[82] and a significant challenge for the neuromuscular system relative to attenuating potentially harmful forces away from bone/cartilage/ligament tissue.[82,83] In DLLs after catching a pass, TTPVGRFs were 48.8ms.[16] In SLLs with and without catching a pass, TTPVGRFs were 30.6-42.1ms[16,17] and 43.7ms, [81] respectively.

The peak braking force (BF) refers to horizontal ground reaction forces (HGRFs) which push players posteriorly when landing with anteriorly-directed momentum.[84] The BF is of interest for the same reason as the VGRF and because it provides additional insight into potentially harmful tissue loading factors.[17,82,85] For DLLs after catching a pass, BFs were 1.7BW.[16] For SLLs after catching a pass, BFs were 1.4-3.3BW.[16,17] The time-to-peak BF (TTPBF) is of interest for the same reason as the TTPVGRF. In DLLs after catching a pass, TTPBFs were 44.3ms.[16] In SLLs after catching a pass, TTPBFs were 23.9-44.7ms.[16,17]

External and internal moments come from outside (e.g. VGRF) and inside (e.g. muscles) the body, respectively, and tend to cause joint rotation.[18,19] Peak external moments are of interest because they estimate the tensile forces experienced by ligaments.[19,86] In biomechanical modelling, external and internal moments balance each other and are equal and opposite in direction.[18,19] Studies which only report knee internal moments of a specific size can, therefore, assume the knee experienced external moments of the same magnitude. For DLLs without catching a pass, knee internal adduction moments (opposing knee external abduction moments) were 0.38Nm/kg.[87] For SLLs after catching a pass, knee internal adduction moments (opposing knee external abduction moments) were near 0.40Nm/kg.[85]

Frontal plane peak knee abduction angles are of interest because higher angles result in higher ACL and MCL stress/strain.[77–80] As ligament strain increases with higher abduction angles, the point of ligament damage gets closer.[88] For DLLs with and without catching a pass, knee abduction angles were 8.6°[89] and 12.1°,[87] respectively. For SLLs after catching a pass, knee abduction angles were 5.2°.[89]

Sagittal plane lower-limb joint displacement is of interest because small displacements are linked to 'stiff' landings and large displacements are linked to 'soft' landings.[90–92] As for short TTPVGRFs, stiff landings are associated with higher tissue peak loads and rate-of-loading than soft landings.[90,91,93] In DLLs without catching a pass, knee flexion at initial contact (IC) was 21.1° and at peak flexion was 85.2°, giving a mean displacement of 64.1°.[87] In SLLs after catching a pass, knee flexion at IC was near 15° and at 50% of stance phase was near 60°.[85] In other SLLs after catching a pass, knee flexion at IC was 16.3° and at peak flexion was 60.3°, giving a mean displacement of 44.1°.[89]

When the kinetic and kinematic profile of netball landings is familiar, 'high-risk' events that contain the potential for excessive loading of knee ligaments and injury can be better identified and understood. Decreased lower-limb flexion displacement during landing is related to increased VGRFs,[94–96] increased knee abduction moments,[94,96] and increased ACL tensile loads.[93] Increased VGRFs are related to increased knee anterior shear forces.[97,98] Increased knee external abduction moments are related to increased ACL and MCL loads.[77–79] Higher rates-of-loading of the knee ligaments are more likely to cause tissue failure than lower rates-of-loading.[99,100] Thus, netball DLLs and SLLs contain high-risk biomechanical features that contain the potential for noncontact ACL and MCL injury.

DEVELOPING NONCONTACT KNEE LIGAMENT INJURY PREVENTION SCREENING PROCEDURES

Having combined real-world observation of noncontact knee injury mechanisms (descriptive research) with laboratory-based study of landing tasks that simulate high-risk events (cross-sectional research), specific screening procedures can be considered relative to selected biomechanical features that contain the potential for noncontact knee ligament injury (Figure 2). The injury-inducing events and high-risk tasks discussed above require sophisticated equipment (e.g. 3D motion analysis) to determine kinetic/kinematic features (e.g. external abduction moment). Because such equipment is not typically available to community-based sports physical therapists, clinic-based 'surrogate' procedures related to 3D kinetic/kinematic features are required. Surrogate procedures are chosen using cross-sectional studies employing correlation or simple linear regression designs (Figure 2). Prospective studies reporting associations between intrinsic risk factors and future injury are also used to identify potential screening procedures (Figure 2). Alongside cross-sectional and prospective research, clinicians' opinions (i.e. critical thinking[101] + clinical reasoning[102]) derived using basic kinesiological modelling[103,104] (e.g. identifying which muscles control joint motions in specific directions) can be additionally employed (Figure 2). Integrating different types of research (descriptive + cross-sectional + prospective + opinion) results in rich overall decision-making.[54,69,72] Because little netball correlation, simple linear regression, or prospective research has been performed, the design of netball-specific knee ligament injury prevention screening draws from other related studies.

The Beighton score includes joint assessments to identify individuals with general joint hypermobility (GJH),[105,106] which is prevalent in child[107] and adult[108,109] netball players. No published work has examined relationships between Beighton scores and knee biomechanical characteristics derived from 3D motion analysis of DLL/SLL tasks. In contrast, GJH is prospectively linked to an increased risk of all knee injuries[110] and noncontact ACL injuries[111] in athletic females. General joint hypermobility assessment using the Beighton score procedures may be useful for identifying players predisposed to increased risk for noncontact knee ligament injury.

The ankle is an important component in the lower-limb kinetic chain.[112] In DLLs, decreased straight-knee ankle dorsiflexion (DF) ROM measured with a goniometer was related to increased VGRFs, knee external abduction moments, and knee abduction displacements.[113,114] In DLLs, decreased bent-knee ankle dorsiflexion ROM measured with the weight-bearing lunge test (WBLT) was related to decreased knee flexion displacements.[115] No prospective work has reported an association between ankle dorsiflexion ROM and noncontact knee ligament injury. Screening ankle DF ROM with a goniometer or the WBLT may provide data for identifying players predisposed to sub-optimal landing biomechanics.

The lateral trunk muscles influence pelvis position and motion[104,116] and pelvis position and motion influence knee biomechanics.[104,117] In SLLs, decreased trunk rotation strength measured with an isokinetic dynamometer (IKD) was related to increased knee abduction displacement.[118] In a single-leg squat (SLS), decreased isometric side-bridge strength measured with a handheld dynamometer (HHD)[119] and decreased strength-endurance measured via holding-time[120] were related to increased knee abduction angles. In prospective work, large trunk lateral flexion displacements following laterally-directed perturbations were linked to higher odds for experiencing noncontact ACL injury.[121] Screening lateral trunk muscle performance with a HHD or isometric holding-times may have utility for identifying players predisposed to sub-optimal landing biomechanics and risk for noncontact knee ligament injury.

Lower-limb muscles generate internal moments that absorb foot-ground impact forces[19] and stress-shield skeletal tissues from excessive loads.[122] Outside 3D motion analysis, lower-limb internal moment generating ability is inferred using strength tests.[123] For SLLs, decreased isometric hip abduction strength measured with a HHD was related to increased knee abduction angles.[124] For SLLs, decreased isometric hip external rotation (ER) strength measured with a HHD was related to increased VGRFs, knee external abduction moments, knee abduction angles, and knee anterior shear forces,[86,124] and decreased isometric knee ER strength measured with an IKD was related to increased knee IR angles.[125] For SLLs, decreased SLS strength measured with a barbell and decreased isometric knee flexion strength measured with an IKD were related to increased knee abduction and IR angles.[126] In prospective research, decreased lower-limb strength estimated with one-repetition-maximum (1RM) barbell back-squats was associated with increased odds for traumatic knee injuries.[127] In other prospective and case-control work, decreased isometric hip abduction and ER strength estimated with a HHD[128] and decreased knee flexion strength estimated with an IKD[129] were associated with noncontact ACL injuries. Screening hip and knee muscle strength with double- and single-leg strength tests may be useful for identifying players predisposed to sub-optimal landing biomechanics and risk for noncontact knee ligament injury. Considering kinesiological modelling, given that the quadriceps and gastrocnemius/soleus control knee flexion and ankle DF, respectively,[103,104] and the dissipation of landing impact forces,[92] screening of knee extensor[130] and ankle plantarflexor[131,132] muscle strength is wise. Isokinetic dynamometers and HHDs can be expensive and not easily available to community-based practitioners.[130] Alternatively, leg press, knee flexion, and knee extension resistance machines can be more readily accessible.[130] Single-leg 1RM strength tests can be performed with netball players in local communities and contribute to knee injury prevention procedures.[130,133] Combining free-weight and resistance machine procedures for double-/single-leg strength testing may be the most thorough approach.[66]

Balance is the process of maintaining the body's center-of-mass and center-of-pressure within its base-of-support via internal moments countering external moments that act to destabilize the body and its joints.[134] Balance is a sensorimotor process involving proprioceptive, visual, and vestibular sensory information used by the central nervous system to adjust motor output and maintain postural equilibrium.[134] For SLLs, increased single-leg stance center-of-pressure excursion (worse balance) was related to increased knee external abduction moments.[135] In prospective studies, reduced dynamic balance defined by three (anterior/posteromedial/posterolateral) of the six directions in the Star Excursion Balance Test (SEBT) was associated with increased odds of lower-limb injuries including knee sprains.[136] The SEBT has since been modified to use just the anterior, posteromedial, and posterolateral directions in the form of the Y-Balance Test (YBT).[137] Reduced YBT performance defined by a reduced anterior/posteromedial/posterolateral composite score[138] and a reduced anterior score alone[139] have been prospectively linked to lower-limb noncontact injuries. Reduced static balance defined by a computer-force plate system has been associated with increased ACL injury frequency.[140] Screening single-leg balance (SLB) with procedures such as the SEBT, YBT, and timed eyes-open/eyes-closed balance may provide data for identifying players predisposed to sub-optimal landing biomechanics and risk for noncontact knee ligament injury. Timed eyes-closed SLB tests have been used in preseason screening for community-level netball players.[25,141]

Neurocognitive performance refers to cerebral neural functions contributing to cognition and includes processes such as visual attention, visual memory, verbal memory, processing speed, reaction time, and dual-tasking.[142,143] Neurocognitive performance is integrated with sensorimotor functions (proprioception, neuromuscular control) to activate skeletal muscle and maintain joint stability during athletic tasks.[142] No published work has examined relationships between measures of neurocognitive performance and knee biomechanical characteristics derived from 3D motion analysis of DLL/SLL tasks. One study, however, reported that decreased neurocognitive performance (decreased visual memory) was associated with increased knee abduction angles during sidestep cutting.[144] Preseason neurocognitive assessment using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) procedures[145–147] was linked to in-season lower-limb sprains[148] and noncontact ACL injuries.[149] Screening neurocognitive performance with the ImPACT procedures or other computerized systems may have utility for identifying players predisposed to sub-optimal knee biomechanics and risk for noncontact knee ligament injury.

Movement screening is the process of assessing athletes' kinematic patterns relative to the biomechanics of injury mechanisms and high-risk events that contain the potential for noncontact knee ligament injury. Because 3D motion analysis equipment is not easily accessible to community-based practitioners, 2D motion analysis procedures have been developed using commonly available high-definition video cameras. During landings, 2D measurements of frontal plane knee kinematics (e.g. knee abduction angle) *are not* related to 3D measurements.[150–152] During a SLS, however, 2D measurements of frontal plane knee kinematics *are* related to 3D measurements.[150,153,154] Therefore, 2D motion analysis *is not* advocated for assessing DLL/SLL frontal plane knee kinematics.[150–152] Conversely, use of a SLS in netball knee injury prevention screening *is* advocated because its knee biomechanical characteristics are related to those in netball-specific leap-landings.[155] If high-definition video cameras are not accessible, generic observational DLL (e.g. Landing Error Scoring System [LESS]-Real Time [LESS-RT],[156] Tuck Jump Assessment [TJA][157]), SLL (e.g. Qualitative Analysis of Single-Leg Loading[158]), and SLS[158,159] movement screens have been developed where the observer visually scores the athlete's hip-knee-ankle kinematics according to pre-defined criteria. Generic DLL movement screens such as the LESS and TJA are not related to the biomechanics of netball-specific SLLs.[160] One group reported the reliability of the 'Netball Movement Screening Tool' (NMST) which contains 10 tasks deemed relevant to assessing netball knee injury risk.[161] The NMST has not been used further beyond another group who employed the NMST to evaluate outcomes from a performance training program.[162] For prospective work, increased trunk ipsilateral lateral flexion and knee abduction measured with 2D motion analysis during a SLL were associated with increased frequency of noncontact knee soft tissue injury.[163] Increased "dynamic knee valgus" measured with 2D motion analysis during a SLL was evident in female athletes who later experienced a noncontact ACL injury compared to those who did not.[164] Poor (higher) LESS scores have been prospectively associated with increased frequency of noncontact ACL injury.[165] Screening whole-body and knee kinematics patterns with procedures such as 2D motion analysis and observational movement screens may be useful for identifying netball players predisposed to sub-optimal landing biomechanics and risk for noncontact knee ligament injury.

The lower-limb functional performance test (FPT) includes hop, leap, jump, linear-sprint, change-of-direction, and agility tasks.[166] In knee injury prevention, single-leg FPTs are recommended to isolate each lower-limb and expose unilateral deficits that can remain hidden in double-leg tasks.[166] In netball, SLL versus DLL occurs on 58.5-67.1% of occasions[14,167] and, therefore, single-leg FPTs are important components of netball-specific knee injury prevention screening. Single-leg FPTs (e.g. hop, leap) recreate the joint compression/shear/torsion/rotation forces encountered in sport-specific activity[166,168,169] and are measured using performance-related variables such as distance (centimeters) or time (seconds).[166,170,171] No study has examined the association between single-leg FPT performance-related variables and knee biomechanical characteristics derived from 3D motion analysis of DLL/SLL tasks. For prospective research, athletes with a single-hop-for-distance mean distance of ≤64% of height for either limb were at increased risk of thigh and knee injuries[172] and athletes with a side-to-side difference (asymmetry) of >10% for the single-hop-for-distance experienced more frequent noncontact ankle and foot trauma.[173] Screening single-leg FPTs may provide data for identifying netball players predisposed to increased risk of noncontact knee ligament injury. Further considerations include that some FPTs may be more suited to assessing lower-limb force production (e.g. vertical-hop) versus force absorption (e.g. horizontal-hop) ability.[166,174] The shared variance between vertical-hop and horizontal-hop performance in netball players is low and, therefore, such tests capture different aspects of lower-limb motor-performance.[174] Unidirectional (e.g. triple-hop-for-distance)[171] and multidirectional (e.g. zig-zag hop)[170,171] repeated hop single-leg FPTs may also be useful for adding greater repeated impact and frontal and transverse plane challenges to the knee joint.[166,170] Recently, screening of a community-level adult netball team using single-leg FPTs revealed that side-to-side asymmetries of >10% for the triple-hop-for-distance, single-hop-for-distance, and vertical-hop existed for 8.7%, 8.7%, and 52.2% of players, respectively.[141] Given such considerations, netball knee injury prevention screening may require a selection of different single-leg hop FPTs.

DISCUSSION: CLINICAL INTEGRATION AND APPLICATION

Based on the different types of research cited in the previous section, suggested noncontact knee ligament injury intrinsic risk factor screening procedures appear in Table 3. In terms of integrating and applying such procedures in sports physical therapy practice in netball, it may not be necessary to perform all tests in Table 3. Clinicians can decide for themselves which procedures are viable based on their local logistical constraints (e.g. equipment/personnel/finance/time availability).[66] When a battery of procedures has been assembled, and given the recursive nature of netball training and competition, serial screening should occur at appropriate timepoints across a season/year to reveal changes in a player's risk profile.[50,52,65,66]

The majority of screening procedures in Table 3 are for modifiable intrinsic risk factors for which conservative interventions are applicable. One intrinsic risk factor, the Beighton score for GJH,[105,106] is nonmodifiable. The value of including such a nonmodifiable risk factor is that further supplementary sensorimotor control interventions for enhancing knee functional joint stability can be considered for those classed as having GJH.[175]

When a battery of screening procedures has been administered, the sports physical therapist should design a targeted intervention program to address intrinsic risk factors that are of specific concern (e.g. hip abductor muscle strength, balance, reaction time).[50,141,176–179] These interventions then contribute to stage three of the sequence of prevention.[49] During stage three and across the competitive season, noncontact knee ligament injury incidence requires monitoring. At the end of the season, noncontact knee ligament injury incidence is compared to that of previous seasons; this represents stage four of the sequence of prevention[49] and is a critical evaluative step in any primary prevention strategy for injury.[44–46,48,49] Future research should endeavour to identify modifiable intrinsic risk factors for noncontact knee ligament injury specifically in netball. Research should be performed for all levels of the game and all competitive age groups.

SUMMARY

Netball is a team court-sport played worldwide and becoming more popular in the US. Noncontact knee ligament injuries are common due to a knee abduction collapse during landing. High-risk landing events that contain the biomechanical potential for noncontact knee ligament injury are common in netball. Cross-sectional research, prospective research, and kinesiological modelling provide insight into modifiable intrinsic risk factors linked to high-risk landing biomechanics and actual noncontact knee ligament injury incidence. This clinical commentary has described how theoretical principles (injury control, sequence of prevention, principles of screening in injury prevention, multifactorial model of injury etiology, complex systems theory, systems science), different types of research (descriptive, analytic-observational), and different levels of evidence (prospective, cross-sectional, clinician's opinion) underpin a rational clinical reasoning process that develops screening procedures for community-level netball noncontact knee ligament injury prevention. An example of how such theories, research, and evidence can be applied by the sports physical therapist has been provided in the form of detailed explanations for suggested screening procedures (Figure 2, Table 3) and comments on the need for repeated screening at strategic timepoints across a season/year.

CONFLICT OF INTEREST STATEMENT

The author declares there are no conflicts of interest.

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Table 3: Suggested netball-specific noncontact knee ligament injury prevention screening tests*†

Characteristic	Test	Example Variable	Related Study Reference number
General joint hypermobility	Beighton score	Composite score‡	105
Ankle joint DF mobility	Straight-knee passive DF ROM with	°	113, 114
	a goniometer		
	Weightbearing lunge test	cm	115
Trunk muscle strength	Side-bridge isometric strength with	%BW	119
	a HHD		
	Side-bridge isometric hold	s	120
Lower-limb muscle	1RM modified barbell single-leg squat	%BW, LSI, A-A	126
strength			
	1RM single-leg leg-press	%BW, LSI, A-A	130
Hip muscle strength	Side-lying straight-leg hip abduction	%BW, LSI, A-A	124
	isometric strength with a HHD		
	Prone bent-knee hip ER isometric	%BW, LSI, A-A	124
	strength with a HHD		
Knee muscle strength	1RM single-leg knee extension	%BW, LSI, A-A	130
	1RM single-leg knee flexion	%BW, LSI, A-A	130
Ankle muscle strength	1RM standing single-leg straight-leg	%BW, LSI, A-A	131
	calf-raise		
	1RM seated single-leg bent-leg	%BW, LSI, A-A	132
	calf-raise		
Balance	Star Excursion Balance Test	%LL, LSI, A-A	136
	Anterior/posteromedial/ posterolateral		
	Y-Balance Test	Composite score‡	138
		cm, A-A	139
	Eyes-closed single-leg balance	s, LSI, A-A	25, 141

Neurocognitive performance	ImPACT	Composite score‡	146, 147
Lower-limb movement	2D high-definition video single-leg	Peak ipsilateral	163, 164
patterns	drop-vertical-jump	trunk lean angle, °	
		Peak knee	
		abduction angle, °	
	2D high-definition video single-leg	Peak ipsilateral	150
	squat	trunk lean angle, °	
		Peak knee	
		abduction angle, °	
	LESS-RT	Composite score‡	156
	QASLL	Composite score‡	158
Lower-limb functional	Single-hop-for-distance	%LL, %H, LSI, A-A	141, 171
performance			
	Triple-hop-for-distance	%LL, %H, LSI, A-A	141, 171
	Adapted crossover hop for distance	%LL, %H, LSI, A-A	170
	Vertical-hop	%LL, %H, LSI, A-A	141

* Modified from reference 66.
† All single-leg tests are performed for both right and left sides.
‡ = see Related Study citation for scoring system.
DF = dorsiflexion; ROM = range-of-motion; ° = degrees; cm = centimeters; HHD = handheld dynamometer;
%BW = percentage of bodyweight = (weight lifted (kg) ÷ bodyweight (kg)) × 100; s = seconds;
1RM = one repetition maximum; LSI = limb symmetry index (%) = (right side score ÷ left side score) × 100;
A-A = absolute-asymmetry = LSI of 100% − player's actual LSI (with '+' or '−' sign then removed);
ER = external rotation; %LL = percentage of leg-length = (distance hopped (cm) ÷ leg-length (cm)) × 100;
ImPACT = Immediate Post-Concussion Assessment and Cognitive Testing; 2D = two dimensional;
LESS-RT = Landing Error Scoring System-Real Time; QASLL = Qualitative Analysis of Single-Leg Loading;
FPT = functional performance test;
%H = percentage of standing height = (distance hopped (cm) ÷ standing height (cm)) × 100.

REFERENCES

1. International Netball Federation. Regions and Members. International Netball Federation. https://netball.sport/inside-inf/regions-members. Published 2020. Accessed June 24, 2020.

2. International Netball Federation. History of Netball. International Netball Federation. https://netball.sport/game/history-of-netball. Published 2020. Accessed June 24, 2020.

3. England Netball. *England Netball Annual Report 2016-2017*. Leicestershire; 2018.

4. Sport England. Active Lives Survey. Sport England. https://www.sportengland.org/know-your-audience/data/active-lives. Published 2020. Accessed June 24, 2020.

5. Netball Australia. *Annual Report 2018*. Australia: Netball Australia; 2018.

6. Netball England. *England Netball Annual Report 2016-2017*. Leicestershire; 2018.

7. Netball America. Netball Fact Sheet. Netball America. https://netballamerica.com/communications/fact-sheet/. Published 2020. Accessed June 24, 2020.

8. International University Sports Federation. 2nd World University Netball Championship. International University Sports Federation. https://www.fisu.net/netball/2nd-wuc-netball. Published 2020. Accessed June 24, 2020.

9. Netball America. USA Team and USA Representative Teams. Netball America. https://netballamerica.com/training-room/usa-team/. Published 2020. Accessed June 24, 2020.

10. Parkkari J, Kannus P, Natri A, et al. Active living and injury risk. *Int J Sports Med*. 2004;25(3):209-216.

11. Rose M, Emery C, Meeuwisse W. Sociodemographic predictors of sport injury in adolescents. *Med Sci Sports Exerc*. 2008;40(3):444-450.

12. Posty E, Trigstedy S, Riekenayz J, et al. The association of sport specialization and training volume with injury history in youth athletes. *Am J Sports Med*. 2017;45(6):1405-1412.

13. International Netball Federation. *Rules of Netball*. England: International Netball Federation; 2020.

14. Hopper D, Lo S, Kirkham C, Elliott B. Landing patterns in netball: analysis of an international game. *Br J Sports Med*. 1992;26(2):101-106.

15. Williams R, O'Donoghue P. Lower limb injury risk in netball: a time-motion analysis investigation. *Journal of Human Movement Studies*. 2005;49(5):315-331.

16. Otago L. Kinetic analysis of landings in netball: is a footwork rule change required to decrease ACL injuries? *J Sci Med Sport*. 2004;7(1):85-95.

17. Steele J, Lafortune M. A kinetic analysis of footfall patterns at landing in netball. *Australian J Sci Med Sport*. 1989;21(1):10-13.

18. Hall S. *Basic Biomechanics*. 7th ed. New York: McGraw-Hill Higher Education; 2014.

19. Perry J, Burnfield J. *Gait Analysis. Normal and Pathological Function*. 2nd ed. New Jersey: SLACK Inc.; 2010.

20. Hopper D. A survey of netball injuries and conditions related to these injuries. *Aust J Physio*. 1986;32(4):231-239.

21. Hopper D, Elliott B. Lower limb and back injury patterns of elite netball players. *Sports Med*. 1993;16(2):148-162.

22. Pillay T, Frantz JM. Injury prevalence of netball players in South Africa: The need for injury prevention. *S African J Physiother*. 2012;68(3):7-10.

23. Smith MMF, Mendis MD, Parker A, Grantham B, Stewart S, Hides J. Injury surveillance of an Australian community netball club. *Phys Ther Sp*. 2020;44:41-46.

24. Flood L, Harrison JE. Epidemiology of basketball and netball injuries that resulted in hospital admission in Australia, 2000–2004. *Med J Aust*. 2009;190(2):87-90.

25. Hopper D, Hopper J, Elliott B. Do selected kinanthropometric and performance variables predict injuries in female netball players. *J Sports Sci*. 1995;13(3):213-222.

26. Hopper D, Elliott B, Lalor J. A descriptive epidemiology of netball injuries during competition: a five year study. *Br J Sports Med*. 1995;29(4):223-228.

27. Stuelcken M, Mellifont D, Gorman A, Sayers M. Mechanisms of anterior cruciate ligament injuries in elite women's netball: a systematic video analysis. *J Sports Sci*. 2016;34(16):1516-1522.

28. Finch C, Cassell E. The public health impact of injury during sport and active recreation. *J Sci Med Sport*. 2006;9(6):490-497.

29. Janssen K, Orchard J, Driscoll T, van Mechelen W. High incidence and costs for anterior cruciate ligament reconstructions performed in Australia from 2003–2004 to 2007–2008: time for an anterior cruciate ligament register by Scandinavian model? *Scand J Med Sci Sports*. 2012;4(22):495-501.

30. Otago L, Peake J. The role of insurance data in setting priorities for netball injury prevention strategies. *J Sci Med Sport*. 2007;10(2):105-109.

31. Loes M de, Dahlstedt LJ, Thomée R. A 7 - year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scand J Med Sci Sports*. 2000;10(2):90-97.

32. Lubowitz JH, Appleby D. Cost-Effectiveness Analysis of the Most Common Orthopaedic Surgery Procedures: Knee Arthroscopy and Knee Anterior Cruciate Ligament Reconstruction. *Arthroscopy*. 2011;27(10):1317-1322.

33. Freedman K, Glasgow M, Glasgow S, Bernstein J. Anterior cruciate ligament injury and reconstruction among university students. *Clin Orthop Relat Res*. 1998;(356):208-212.

34. Trentacosta N, Vitale M, Ahmad C. The effects of timing of pediatric knee ligament surgery on short-term academic performance in school-aged athletes. *Am J Sports Med*. 2009;37(9):1684-1691.

35. England Netball. Top 10 on the 10th – Injury Prevention. England Netball. https://www.englandnetball.co.uk/coachblog/top-10-10th-injury-prevention/. Published 2016. Accessed June 24, 2020.

36. Lie MM, Risberg MA, Storheim K, Engebretsen L, Britt EØ. What's the rate of knee osteoarthritis 10 years after anterior cruciate ligament injury? An updated systematic review. *Br J Sports Med*. 2019;53(18):1162-1167.

37. Lohmander L, Englund P, Dahl L, Roos E. The long-term consequence of anterior cruciate ligament and meniscus injuries: Osteoarthritis. *Am J Sports Med*. 2007;35(10):1756-1769.

38. Mainwaring LM, Hutchison M, Bisschop SM, Comper P, Richards DW. Emotional response to sport concussion compared to ACL injury. *Brain Inj*. 2010;24(4):589-597.

39. Wu H, Liu M, Dines J, Kelly J, Garcia G. Depression and psychiatric disease associated with outcomes after anterior cruciate ligament reconstruction. *World J Orthop*. 2016;7(11):709-717.

40. Baum AL. Suicide in Athletes: A Review and Commentary. *Clin Sports Med*. 2005;24(4):853-869.

41. Smith A, Milliner E. Injured athletes and the risk of suicide. *J Athl Train*. 1994;29(4):337-341.

42. Burns PB, Rohrich RJ, Chung KC. The levels of evidence and their role in evidence-based medicine. *Plastic Reconstr Surg*. 2011;128(1):305-310.

43. Avery J. Accident prevention-injury control-injury prevention-or whatever? *Inj Prev*. 1995;1(1):10.

44. Rivara F. Introduction: the scientific basis for injury control. *Epidemiol Rev*. 2003;25:20-23.

45. Johnston BD, Rivara FP. Injury control: new challenges. *Pediatrics in Review*. 2003;24(4):111-118.

46. Barss P, Smith G, Baker S, Mohan D. *Injury Prevention: An International Perspective*. New York: Oxford University Press; 1998.

47. Bolling C, van Mechelen W, Pasman HR, Verhagen E. Context matters: revisiting the first step of the "sequence of prevention" of sports injuries. *Sports Med*. 2018;48(10):2227-2234.

48. Finch C. A new framework for research leading to sports injury prevention. *J Sci Med Sport*. 2006;9(1):3-9.

49. van Mechelen W, Hlobil H, Kemper H. Incidence, severity, etiology and prevention of sports injuries: A review of concepts. *Sports Med*. 1992;14(2):82-99.

50. Verhagen E, van Dyk N, Clark N, Shrier I. Do not throw the baby out with the bathwater; screening can identify meaningful risk factors for sports injuries. *Br J Sports Med*. 2018;52(19):1223-1224.

51. Meeuwisse W. Assessing causation in sport injury: A multifactorial model. *Clin J Sport Med*. 1994;4(3):166-170.

52. Bittencourt N, Meeuwisse W, Mendonça L, Nettel-Aguirre A, Ocarino J, Fonseca S. Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition - narrative review and new concept. *Br J Sports Med*. 2016;50(21):1309-1314.

53. Drolet BC, Lorenzi NM. Translational research: understanding the continuum from bench to bedside. *Transl Res*. 2011;157(1):1-5.

54. Mabry PL, Olster DH, Morgan GD, Abrams DB. Interdisciplinarity and systems science to improve population health: a view from the NIH Office of Behavioral and Social Sciences Research. *Am J Prev Med*. 2008;35(2):S211-S224.

55. Mace SE, Gerardi MJ, Dietrich AM, et al. Injury prevention and control in children. *Ann Emerg Med*. 2001;4(38):405-414.

56. McLeod R, Stockwell T, Rooney R, Stevens M, Phillips M, Jelinek G. The influence of extrinsic and intrinsic risk factors on the probability of sustaining an injury. *Accid Anal Prev*. 2003;35(1):71-80.

57. Banerjee A, Jadhav S, Bhawalkar J. Probability, clinical decision making and hypothesis testing. *Ind Psychiatry J*. 2009;18(1):64-69.

58. Portney L, Watkins M. *Foundations of Clinical Research: Applications to Practice*. 3rd ed. New Jersey: Pearson/Prentice Hall; 2009.

59. Di Costanzo C. Science and rights: The "clinical reasoning" within health needs assessment. *GSTF Journal of Law and Social Sciences*. 2012;1(2):84-89.

60. Waite M. *Oxford English Dictionary*. 7th ed. Oxford: Oxford University Press; 2012.

61. Neely F. Intrinsic risk factors for exercise-related lower limb injuries. *Sports Med*. 1998;26(4):253-263.

62. Emery CA. Risk factors for injury in child and adolescent sport: A systematic review of the literature. *Clin J Sport Med*. 2003;13(4):256-268.

63. Rothman K, Greenland S, Lash T. *Modern Epidemiology*. 3rd ed. Philadelphia: Lippincott Williams and Wilkins; 2008.

64. Porta M. *A Dictionary of Epidemiology*. 6th ed. Oxford: Oxford University Press; 2014.

65. Meeuwisse WH, Tyreman H, Hagel B, Emery C. A dynamic model of etiology in sport injury: the recursive nature of risk and causation. *Clin J Sport Med*. 2007;17(3):215-219.

66. Mullally E, Clark N. Noncontact knee soft-tissue injury prevention considerations and practical applications for netball players. *Str Condit J*. 2020;In press. doi:10.1519/SSC.0000000000000609

67. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med*. 2005;39(6):324-329.

68. Gallagher R, Appenzeller T, Normile D. Beyond reductionism. *Science*. 1999;284(5411):79.

69. Lich K, Ginexi E, Osgood N, Mabry P. A call to address complexity in prevention science research. *Prev Sci*. 2013;14(3):279-289.

70. Philippe P, Mansi O. Nonlinearity in the epidemiology of complex health and disease processes. *Theor Med Bioeth*. 1998;19(6):591-607.

71. Pearce N, Merletti F. Complexity, simplicity, and epidemiology. *Int J Epidemiol*. 2006;35:515-519.

72. Mabry PL, Marcus SE, Clark PI, Leischow SJ, M'Endez D. Systems science: A revolution in public health policy research. *Am J Public Health*. 2010;100(7):1161-1163.

73. Shiell A, Hawe P, Gold L. Complex interventions or complex systems? Implications for health economic evaluation. *BMJ*. 2008;336(7656):1281-1283.

74. Marshall S, Padua D, McGrath M, Hewett T, Shultz S, Griffin L. Incidence of ACL injury. In: *Understanding and Preventing Noncontact ACL Injuries*. Illinois: Human Kinetics; 2007:5-29.

75. Dempsey A, Elliott B, Munro B, Steele J, Lloyd D. Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. *Clin Biomech*. 2012;27(5):466-474.

76. Krosshaug T, Nakamae A, Boden B, et al. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007;35(3):359-367.

77. Markolf K, Burchfield D, Shapiro M, Shepard M, Finerman G, Slauterbeck J. Combined knee loading states that generate high anterior cruciate ligament forces. *J Orthop Res*. 1995;13(6):930-935.

78. Shin C, Chaudhari A, Andriacchi T. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Med Sci Sports Exerc*. 2011;43(8):1484-1491.

79. Shin CS, Chaudhari AM, Andriacchi TP. The effect of isolated valgus moments on ACL strain during single-leg landing: A simulation study. *J Biomech*. 2009;42(3):280-285.

80. Gardiner J, Weiss J, Rosenberg T. Strain in the human medial collateral ligament during valgus loading of the knee. *Clin Orthop Relat Res*. 2001;(391):266-274.

81. Hopper D, McNair P, Elliott B. Landing in netball: effects of taping and bracing the ankle. *Br J Sports Med*. 1999;33(6):409-413.

82. Steele J. Biomechanical factors affecting performance in netball. Implications for improving performance and injury reduction. *Sports Med*. 1990;10(2):88-102.

83. Whiting W, Zernicke R. *Biomechanics of Musculoskeletal Injury*. 2nd ed. Illinois: Human Kinetics; 2008.

84. Fietzer A, Chang Y, Kulig K. Dancers with patellar tendinopathy exhibit higher vertical and braking ground reaction forces during landing. *J Sports Sci*. 2012;30(11):1157-1163.

85. Stuelcken M, Greene A, Smith R, Vanwanseele B. Knee loading patterns in a simulated netball landing task. *Eur J Sport Sci*. 2013;13(5):475-482.

86. Lawrence R, Kernozek T, Miller E, Torry M, Reuteman P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clin Biomech*. 2008;23(6):806-813.

87. Sinclair J, Vincent H, Richards J. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements. *Phys Ther Sp*. 2017;23:93-98.

88. Woo S, Abramowitch S, Kilger R, Liang R. Biomechanics of knee ligaments: injury, healing, and repair. *J Biomech*. 2006;39(1):1-20.

89. Sinclair J, Taylor PJ, Foxcroft H. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during single-and double-limb post-catch deceleration strategies in university netballers. *Sport Sci Health*. 2019;15(1):215-222.

90. Devita P, Skelly W. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*. 1992;24(1):108-115.

91. Self B, Paine D. Ankle biomechanics during four landing techniques. *Med Sci Sports Exerc*. 2001;33(8):1338-1344.

92. Zhang S, Bates B, Dufek J. Contributions of lower extremity joints to energy dissipation during landings. *Med Sci Sports Exerc*. 2000;32(4):812-819.

93. Laughlin W, Weinhandl J, Kernozek T, Cobb S, Keenan K, O'Connor K. The effects of single-leg landing technique on ACL loading. *J Biomech*. 2011;44(10):1845-1851.

94. Ali N, Rouhi G, Robertson G. Gender, vertical height and horizontal distance effects on single-leg landing kinematics: Implications for risk of non-contact ACL injury. *J Hum Kinet*. 2013;37:27-38.

95. Leppänen M, Pasanen K, Kujala U, et al. Stiff landings are associated with increased ACL injury risk in young female basketball and floorball players. *Am J Sports Med*. 2017;45(2):386-393.

96. Pollard CD, Sigward SM, Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clin Biomech*. 2010;25(2):142-146.

97. Sell TC, Ferris CM, Abt JP, et al. Predictors of proximal tibia anterior shear force during a vertical stop - jump. *J Orthop Res*. 2007;25(12):1589-1597.

98. Yu B, Lin C, Garrett W. Lower extremity biomechanics during the landing of a stop-jump task. *Clin Biomech*. 2006;21(3):297-305.

99. Noyes F, DeLucas J, Torvik P. Biomechanics of anterior cruciate ligament failure: an analysis of strain-rate sensitivity and mechanisms of failure in primates. *J Bone Joint Surg Am*. 1974;56(2):236-253.

100. Crowninshield R, Pope M. The strength and failure characteristics of rat medial collateral ligaments. *J Trauma*. 1976;16(2):99-105.

101. Walker SE. Active learning strategies to promote critical thinking. *J Athl Train*. 2003;38(3):263-267.

102. Huhn K, Gilliland SJ, Black LL, Wainwright SF, Christensen N. Clinical reasoning in physical therapy: a concept analysis. *Phys Ther*. 2019;99(4):440-456.

103. Floyd R. *Manual of Structural Kinesiology*. 19th ed. New York: McGraw-Hill Education; 2015.

104. Neumann D. *Kinesiology of the Musculoskeletal System*. St Louis: Mosby; 2002.

105. Beighton P, Solomon L, Soskolne C. Articular mobility in an African population. *Ann Rheum Dis*. 1973;32(5):413-418.

106. Keer R, Grahame R. *Hypermobility Syndrome*. Philadelphia: Butterworth Heinemann; 2003.

107. Smith R, Damodaran A, Swaminathan S, Campbell R, Barnsley L. Hypermobility and sports injuries in junior netball players. *Br J Sports Med*. 2005;39(9):628-631.

108. Armstrong R. Relative joint contribution to joint hypermobility: The need for careful consideration of lumbar flexion. *Int J Sports Phys Ther*. 2018;13(4):676-686.

109. Soper K, Simmonds JV, Kaz HK, Ninis N. The influence of joint hypermobility on functional movement control in an elite netball population: A preliminary cohort study. *Phys Ther Sp*. 2015;16(2):127-134.

110. Östenberg A, Roos H. Injury risk factors in female European football: a prospective study of 123 players during one season. *Scand J Med Sci Sports*. 2000;10(5):279-285.

111. Uhorchak J, Scoville C, Williams G, Arciero R, St Pierre P, Taylor D. Risk factors associated with noncontact injury of the anterior cruciate ligament: a prospective four-year evaluation of 859 West Point cadets. *Am J Sports Med*. 2003;31(6):831-842.

112. Palmitier RA, An K-N, Scott SG, Chao EY. Kinetic chain exercise in knee rehabilitation. *Sports Med*. 1991;11(6):402-413.

113. Fong C-M, Blackburn JT, Norcross MF, McGrath M, Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. *J Athl Train*. 2011;46(1):5-11.

114. Malloy P, Morgan A, Meinerz C, Geiser C, Kipp K. The association of dorsiflexion flexibility on knee kinematics and kinetics during a drop vertical jump in healthy female athletes. *Knee Surg Sports Traumatol Arthrosc*. 2015;23(12):3550-3555.

115. Howe L, Bampouras T, North J, Waldron M. Ankle dorsiflexion range of motion is associated with kinematic but not kinetic variables related to bilateral drop-landing performance at various drop heights. *Hum Mov Sci*. 2019;64:320-328.

116. Kapandji I. *The Physiology of the Joints. Volume Three. The Trunk and Vertebral Column*. Edinburgh: Churchill Livingstone; 1998.

117. Powers CM. The influence of abnormal hip mechanics on knee injury: a biomechanical perspective. *J Orthop Sports Phys Ther*. 2010;40(2):42-51.

118. Keenan K, Varnell M, Sell T, Abt J, Lephart S. The relationship among trunk strength, trunk power, and knee kinematics during a stop jump cut maneuver. *J Athl Train*. 2015;50(6):S266.

119. Nakagawa T, Maciel C, Serrão F. Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain. *Man Ther*. 2015;20(1):189-194.

120. Willson JD, Ireland ML, Davis I. Core strength and lower extremity alignment during single leg squats. *Med Sci Sports Exerc*. 2006;38(5):945-952.

121. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, Cholewicki J. Deficits in neuromuscular control of the trunk predict knee injury risk: prospective biomechanical-epidemiologic study. *Am J Sports Med*. 2007;35(7):1123-1130.

122. Clark N, Lephart S. Management of the sensorimotor system. The lower limb. In: Jull G, Moore A, Falla D, Lewis J, McCarthy C, Sterling M, eds. *Grieve's Modern Musculoskeletal Physiotherapy*. Edinburgh: Elsevier; 2015:319-327.

123. Dvir Z. *Isokinetics. Muscle Testing, Interpretations, and Clinical Applications*. 2nd ed. Edinburgh: Churchill Livingstone; 2004.

124. Suzuki H, Omori G, Uematsu D, Nishino K, Endo N. The Influence of hip strength on knee kinematics during a single-legged medial drop landing among competitive colleagiate basketball players. *Int J Sports Phys Ther*. 2015;10(5):592-601.

125. Kiriyama S, Sato H, Takahira N. Gender differences in rotation of the shank during single-legged drop landing and its relation to rotational muscle strength of the knee. *Am J Sports Med*. 2009;37(1):168-174.

126. McCurdy K, Walker J, Armstrong R, Langford G. Relationship between selected measures of strength and hip and knee excursion during unilateral and bilateral landings in women. *J Strength Cond Res*. 2014;28(9):2429-2436.

127. Augustsson SR, Ageberg E. Weaker lower extremity muscle strength predicts traumatic knee injury in youth female but not male athletes. *BMJ Open Sport Exerc Med*. 2017;3(1):e000222.

128. Khayambashi K, Ghoddosi N, Straub RK, Powers CM. Hip muscle strength predicts noncontact anterior cruciate ligament injury in male and female athletes: a prospective study. *Am J Sports Med*. 2016;44(2):355-361.

129. Myer GD, Ford KR, Foss KDB, Liu C, Nick TG, Hewett TE. The relationship of hamstrings and quadriceps strength to anterior cruciate ligament injury in female athletes. *Clin J Sport Med*. 2009;19(1):3-8.

130. Clark NC, Reilly LJ, Davies SC. Intra-rater reliability, measurement precision, and inter-test correlations of 1RM single-leg leg-press, knee-flexion, and knee-extension in uninjured adult agility-sport athletes: Considerations for right and left unilateral measurements in knee injury control. *Phys Ther Sp*. 2019;40:128-136.

131. Cen XZ, Liang ZQ, Gao ZX, Lian WL, Wang ZM. The influence of the improvement of calf strength on barefoot loading. *J Biomimetics, Biomaterials Biomed Eng*. 2019;40:16-25.

132. Jamurtas A, Fatouros I, Buckenmeyer P, et al. Effects of plyometric exercise on muscle soreness and plasma creatine kinase levels and its comparison with eccentric and concentric exercise. *J Strength Cond Res*. 2000;14(1):68-74.

133. Clark N, Gumbrell CJ, Rana S, Traole CM, Morrissey MC. The relationship between vertical hop performance and open and closed kinetic chain muscle strength of the lower limb. *J Sports Sci*. 2001;19(1):18-19.

134. Macpherson J, Horak F. Posture. In: Kandel E, Schwartz J, Jessell T, Siegelbaum S, eds. *Principles Neural Science*. New York: McGraw-Hill; 2013:935-938.

135. Durall CJ, Kernozek TW, Kersten M, Nitz M, Setz J, Beck S. Associations between single-leg postural control and drop-landing mechanics in healthy women. *J Sport Rehabil*. 2011;20(4):406-418.

136. Plisky PJ, Rauh MJ, Kaminski TW, Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *J Orthop Sports Phys Ther*. 2006;36(12):911-919.

137. Plisky PJ, Gorman PP, Butler RJ, Kiesel KB, Underwood FB, Elkins B. The reliability of an instrumented device for measuring components of the star excursion balance test. *N Am J Sports Phys Ther*. 2009;4(2):92.

138. Butler RJ, Lehr ME, Fink ML, Kiesel KB, Plisky PJ. Dynamic balance performance and noncontact lower extremity injury in college football players: an initial study. *Sports Health*. 2013;5(5):417-422.

139. Smith C, Chimera N, Warren M. Association of Y Balance Test reach asymmetry and injury in division I athletes. *Med Sci Sports Exerc*. 2015;47(1):136-141.

140. Vrbanić T, Ravlić-Gulan J, Gulan G, Matovinović D. Balance index score as a predictive factor for lower sports results or anterior cruciate ligament knee injuries in Croatian female athletes - preliminary study. *Coll Antropol*. 2007;31(1):253-258.

141. Clark NC, Mullally EM. Prevalence and magnitude of preseason clinically-significant single-leg balance and hop test asymmetries in an English adult netball club. *Phys Ther Sp*. 2019;40:44-52.

142. Herman DC, Zaremski JL, Vincent HK, Vincent KR. Effect of neurocognition and concussion on musculoskeletal injury risk. *Curr Sports Med Rep*. 2015;14(3):194-199.

143. Grindel SH, Lovell MR, Collins MW. The assessment of sport-related concussion: the evidence behind neuropsychological testing and management. *Clin J Sport Med*. 2001;11(3):134-143.

144. Monfort SM, Pradarelli JJ, Grooms DR, Hutchison KA, Onate JA, Chaudhari AM. Visual-spatial memory deficits are related to increased knee valgus angle during a sport-specific sidestep cut. *Am J Sports Med*. 2019;47(6):1488-1495.

145. Iverson G, Lovell M, Collins M. Validity of ImPACT for measuring processing speed following sports-related concussion. *Journal of Clinical and Experimental Neuropsychology*. 2005;27(6):683-689.

146. Lovell M. Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Applications, Inc. https://impacttest.com/. Published 2020. Accessed July 11, 2020.

147. Lovell M, Iverson G, Collins M, et al. Measurement of symptoms following sports-related concussion: reliability and normative data for the post-concussion scale. *Appl Neuropsychol*. 2006;13(3):166-174.

148. Wilkerson GB. Neurocognitive reaction time predicts lower extremity sprains and strains. *Int J Athl Ther Train*. 2012;17(6):4-9.

149. Swanik C, Covassin T, Stearne D, Schatz P. The relationship between neurocognitive function and noncontact anterior cruciate ligament injuries. *Am J Sports Med*. 2007;35(6):943-948.

150. Herrington L, Alenezi F, Alzhrani M, Alrayani H, Jones R. The reliability and criterion validity of 2D video assessment of single leg squat and hop landing. *J Electromyogr Kinesiol*. 2017;34:80-85.

151. Mizner RL, Chmielewski TL, Toepke JJ, Tofte KB. Comparison of two-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump. *Clin J Sport Med*. 2012;22(3):221-227.

152. Sorenson B, Kernozek TW, Willson JD, Ragan R, Hove J. Two-and three-dimensional relationships between knee and hip kinematic motion analysis: single-leg drop-jump landings. *J Sport Rehabil*. 2015;24(4):363-372.

153. Gwynne CR, Curran SA. Quantifying frontal plane knee motion during single limb squats: Reliability and validity of 2 - dimensional measures. *Int J Sports Phys Ther*. 2014;9(7):898-906.

154. Schurr SA, Marshall AN, Resch JE, Saliba SA. Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *Int J Sports Phys Ther*. 2017;12(2):163-172.

155. Fox AS, Bonacci J, Saunders N. The relationship between performance of a single-leg squat and leap landing task: moving towards a netball-specific anterior cruciate ligament (ACL) injury risk screening method. *Sports Biomechanics*. 2018;19(4):1-17.

156. Padua DA, Boling MC, DiStefano LJ, Onate JA, Beutler AI, Marshall SW. Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. *J Sport Rehabil*. 2011;20(2):145-156.

157. Myer GD, Ford KR, Hewett TE. Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athl Ther Today*. 2008;13(5):39-44.

158. Herrington L, Munro A. A preliminary investigation to establish the criterion validity of a qualitative scoring system of limb alignment during single-leg squat and landing. *J Exerc Sports Orthop*. 2014;1(2):1-6.

159. Chmielewski TL, Hodges MJ, Horodyski M, Bishop MD, Conrad BP, Tillman SM. Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *J Orthop Sports Phys Ther*. 2007;37(3):122-129.

160. Fox A, Bonacci J, McLean S, Saunders N. Efficacy of ACL injury risk screening methods in identifying high - risk landing patterns during a sport - specific task. *Scand J Med Sci Sports*. 2017;27(5):525-534.

161. Reid DA, Vanweerd RJ, Larmer PJ, Kingstone R. The inter and intra rater reliability of the Netball Movement Screening Tool. *J Sci Med Sport*. 2015;18(3):353-357.

162. Hopper A, Haff EE, Barley OR, Joyce C, Lloyd RS, Haff GG. Neuromuscular training improves movement competency and physical performance measures in 11–13-year-old female netball athletes. *J Strength Cond Res*. 2017;31(5):1165-1176.

163. Dingenen B, Malfait B, Nijs S, et al. Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Clin Biomech*. 2015;30(8):781-787.

164. Numata H, Nakase J, Kitaoka K, et al. Two-dimensional motion analysis of dynamic knee valgus identifies female high school athletes at risk of non-contact anterior cruciate ligament injury. *Knee Surg Sports Traumatol Arthrosc*. 2018;26(2):442-447.

165. Padua DA, DiStefano LJ, Beutler AI, De La Motte SJ, DiStefano MJ, Marshall SW. The Landing Error Scoring System as a screening tool for an anterior cruciate ligament injury–prevention program in elite-youth soccer athletes. *J Athl Train*. 2015;50(6):589-595.

166. Clark NC. Functional performance testing following knee ligament injury. *Phys Ther Sp*. 2001;2(2):91-105.

167. Lavipour D. Development of a netball specific dynamic balance assessment [MPhil], Auckland University of Technology. 2011.

168. Barber S, Noyes F, Mangine R, DeMaio M. Rehabilitation after ACL reconstruction: function testing. *Orthopedics*. 1992;15(8):969-974.

169. Lephart S, Perrin D, Minger K, Fu F, Gieck J. Sport-specific functional performance tests for the ACL insufficient athlete. *J Athl Train*. 1989;24(2):119.

170. Clark NC, Gumbrell CJ, Rana S, Traole CM, Morrissey MC. Intratester reliability and measurement error of the adapted crossover hop for distance. *Phys Ther Sp*. 2002;3(3):143-151.

171. Noyes F, Barber S, Mangine R. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med*. 1991;19(5):513-518.

172. Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, Mattocks A, Rauh MJ. Preseason functional test scores are associated with future sports injury in female collegiate athletes. *J Strength Cond Res*. 2018;32(6):1692-1701.

173. Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, Rauh MJ. Lower extremity functional tests and risk of injury in Division III collegiate athletes. *Int J Sports Phys Ther*. 2013;8(3):216-227.

174. Clark N, Mullally EM. Relationship between lower limb motor performance measures relevant to knee injury control in uninjured adult netball players. *Knee Surg Sports Traumatol Arthrosc*. 2018;(26):S165-166.

175. Konopinski MD, Jones GJ, Johnson MI. The effect of hypermobility on the incidence of injuries in elite-level professional soccer players: a cohort study. *Am J Sports Med*. 2012;40(4):763-769.

176. Clark NC, Clacher LH. Lower-limb motor-performance asymmetries in English community-level female field hockey players: Implications for knee and ankle injury prevention. *Phys Ther Sp*. 2020;43:43-51.

177. Augustsson SR, Augustsson J, Thomeé R, Karlsson J, Eriksson BI, Svantesson U. Performance enhancement following a strength and injury prevention program: A 26-week individualized and supervised intervention in adolescent female volleyball players. *Int J Sports Sci Coaching*. 2011;6(3):399-417.

178. Steffen K, Engebretsen L. More data needed on injury risk among young elite athletes. *Br J Sports Med*. 2010;44(7):485-489.

179. Śliwowski R, Jadczak Ł, Hejna R, Wieczorek A. The effects of individualized resistance strength programs on knee muscular imbalances in junior elite soccer players. *PloS One*. 2015;10(12):e0144021.