Noncontact Knee Soft Tissue Injury Prevention Considerations and Practical Applications for Netball Players

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Abstract

Netball is a team sport played worldwide. High-risk landing events containing biomechanical potential for noncontact knee soft tissue injury (STI) occur frequently. Subsequently, noncontact knee STI is common following knee abduction collapse during landing tasks. Lower-limb mobility, strength, balance, movement, and hop test characteristics (intrinsic, modifiable risk factors) are associated with high-risk landing biomechanics and noncontact knee STI events. Such risk factors should be considered in netball-specific noncontact knee STI prevention preparticipation screening. Corresponding training methods should be included as indicated in netball-specific multi-modal noncontact knee STI prevention programs. This paper provides insight into noncontact knee injury-related aspects of netball and gives detailed suggestions for injury prevention screening and programming.

1. Introduction

Netball is a predominantly female team sport with hundreds of thousands of players worldwide (74). Netball was conceived in England in 1895, later becoming popular in other British Commonwealth countries (74). In England in 2015, there were 2,945 netball clubs and 104,000 players (41) which increased to 180,200 players by 2017 (41). In 2017, 508,948 players were participating in netball in Australia (124) and 144,358 players competing in New Zealand (126). In the United States (US), netball is relatively new, gaining popularity in the 1980s (122). Now, Netball America has members in 33 states (122). Community-level participation is expected to grow in America following netball's introduction to school curriculums and community centers (122). With increased sport participation comes increased injury frequency (138). Given the growing popularity of community-level netball in the US and worldwide, it is prudent for practitioners to become familiar with injury-related aspects of the game.

Netball is a court-based invasion game played over 15-minute quarters (73). Netball is played indoors and outdoors, involving repeated acceleration, change-of-direction, and jumping/leaping to catch a ball when attempting to score a goal in opponents' territory (70, 163, 184). A unique characteristic of netball is the footwork-rule, restricting players to one-step landings after catching the ball (4, 68, 107). Simply, after touching down with one foot, players can only take one more step with the other foot to decelerate the body - players can then pivot on the touchdown foot and pass the ball to teammates (73). The nature of the footwork-rule and stopping suddenly with one step results in frequent single-leg landings (SLL) with vertical ground reaction forces (VGRFs) up to 5.7 times bodyweight (BW) (165). The VGRF is of interest because it contributes to compression/shear/rotation forces experienced by lower-limb joints (83) and because landings frequently contribute to joint injury in netball, preceding 27.1-73.8% of injury events (67, 68, 141, 161).

Knee injuries represent substantial portions of netball lower-limb injuries (46, 68, 141). Trauma represents 26% of knee injuries referred to emergency rooms (69) and one-third of netball-related hospitalizations (44). Anterior cruciate ligament (ACL) and meniscus tears are common with frequencies of 17.2-22.4% and 4.5-32.7%, respectively (46, 69). Such knee soft tissue injury (STI) results in sequelae including disability (44, 55, 134, 168), socioeconomic burden (30, 44, 77, 134), academic difficulties (53, 176), premature retirement from netball (40), and early-onset osteoarthritis (96, 97). Therefore, strategies are needed to mitigate the burden of injury for players, teams, and society, and extend players' safe participation across the lifespan.

To prevent traumatic knee STI (e.g. ACL sprain/meniscus tear) in netball, practitioners need knowledge of netball-specific knee injury epidemiology and etiology, the biomechanics of netball and 'high-risk events' that may predispose knee STI, and injury prevention considerations. Such knowledge relates to the sequence of injury prevention (8, 43, 177). The purpose of this paper is to explore the frequency of knee STI in netball, the situations/mechanisms of such injuries, the biomechanics of netball-specific movements and high-risk events, to explore injury prevention screening procedures, and to consider injury prevention interventions. Practitioners will find this paper useful for providing insight into injury-related aspects of netball, helping to plan intervention programs that contribute to the prevention of netball knee STI and promote players' safe participation across the lifespan. For this paper, the term 'knee' will relate to the tibiofemoral joint (TFJ).

2. Epidemiology

Epidemiology studies employ different methods to report the frequency and distribution of netball injuries. McManus et al (108) examined injury incidence for Australian community-level players over two seasons. The incidence rate for all injuries was 14.0/1000 player-hours, of which 66% were lower-limb injuries with 17% to the knee. Smith et al (161) examined injury incidence for Australian community-level players over one season. The injury incidence rate was 13.8/1000 player-hours. The majority (60%) were lower-limb injuries, the knee accounting for 16% with a rate of 2.2/1000 player-hours. Pillay and Frantz (141) reported injury prevalence for South African players at a three-day tournament. For all players, 61.8% reported an injury with a rate of 1.9/player. The majority were lower-limb injuries (73.4%) with 28.6% to the knee. Langeveld et al (89) reported injury incidence for South African players at a six-day tournament. Overall, 15% sustained injuries with an incidence of 500.7/1000 player-hours. The knee represented 18.5% of injuries, the majority being ligament sprains.

Other netball-specific injury data include national-level databases. Otago and Peake (134) used insurance data to review netball-related injury claims in Australia over 12 months. Injury incidence was 9.5/1000 players, most (85.3%) being lower-limb injuries. Of all lower-limb injuries, knee ligament sprains/reconstructions/arthroscopies represented >40% of cases. Flood and Harrison (46) used Australian hospitalization data comparing netball and basketball. For females, the knee represented 37.4% of netball injuries and 28.6% of basketball injuries. For ACL sprains and meniscus tears, netball (17.2%, 4.5% respectively) demonstrated higher proportions than basketball (11.1%, 4.1% respectively). Janssen et al (77) used Australian hospitalization data to examine ACL-reconstruction (ACLR) incidence for different sports over five years. For netball and basketball, there were 188/100,000 and 109/100,000 cases, respectively.

Traumatic knee STI represents a substantial portion of netball injuries sustained in regular league matches and short-duration tournaments. Knee injury frequency appears higher in tournaments versus leagues. Where netball and basketball are considered together, netball-related knee STI presents greater burden for healthcare systems than basketball knee STI.

3. Situation and mechanism of knee injury

Knowledge of the situation and mechanism (mechanics) of injury elucidates factors contributing to players' movement patterns at the instant-of-injury (7, 86, 171) (Table 1). Such knowledge informs strategies to prevent future knee STI. Knee STIs themselves are of contact, indirect contact, and noncontact nature (87, 103, 171) (Table 2). Thus, thorough descriptions of injury events require multiple pieces of information. Most netball injuries

(92%) occur during match-play versus training (78) with a respective incidence of 32.2/1000 player-hours and 4.7/1000 player-hours (161). The largest proportion of match-play injuries (68.4%) occur on outdoor courts (78). More knee injuries occur on asphalt (21.4-64.8%) compared to other more yielding surfaces (timber/synthetic/grass) (67, 78, 141). For outdoor injuries, the majority occur in 'fine' weather (94.9%) or when raining (3.5%) (78). Subsequently, match-play on an asphalt surface in fine weather appears as the context and environment which creates the highest risk of knee injury in netball.

Netball injuries occur similarly during offensive (54%) (68) and defensive (59%) (69) match-play. The instant-of-injury coincides predominantly with landing tasks versus change-of-direction tasks. Small proportions of netball injuries (11.5-18.7%) occur during running sudden-stop or cutting maneuvers (68, 171). Such findings are consistent with female basketball where 9% of ACL injuries occurred during cutting (87). In contrast, others report 27.1-73.8% of netball injuries happened during a landing (67, 68, 141, 161). Further netball studies have observed 38% of knee injuries (69) and 81.3% of ACL injuries (171) occurred during landings. Such findings are again consistent with others reporting 59.1% of female basketball ACL injuries occurred during landings (87). Netball and basketball, therefore, appear similar regarding the majority of traumatic knee injuries coincide with landing versus cutting events.

Considering the mechanics of injury, 24-29% of knee injuries are attributed to contact with another player (68, 69, 161). In these studies, however, injuries were not subdivided into direct or indirect contact injuries (Table 2). One study performed detailed video analyses of netball ACL injuries and observed 50% were indirect contact and 50% were noncontact (171). Indirect contact injuries occurred when players were airborne and contesting for the ball just before the instant-of-injury when landing (171). Noncontact injuries occurred as players were landing from receiving a pass (171). Together, studies suggest noncontact knee injuries occur the majority of the time. Therefore, traumatic noncontact knee STIs will be the focus for the remainder of this paper.

Patterns of whole-body kinematics are important because trunk position/motion relative to a support-leg influences forces experienced by the knee. An upright versus forward-inclined trunk during a SLL increases the knee external flexion and abduction moments (29, 157). Trunk lateral flexion (31, 63) and rotation (25, 31) toward an ipsilateral support-leg during a landing increases the knee external abduction moment. Thus, trunk kinematics are coupled with knee biomechanics during landings. Unfavourable sagittal plane coupling (upright trunk + knee flexion) frequently occurs in noncontact ACL injuries (156). Unfavourable frontal plane coupling (trunk ipsilateral lateral flexion + knee abduction) occurred in 83.3% of netball noncontact ACL injuries (4) and female noncontact ACL injuries in other sports (65). Because frontal plane coupling occurs in a support-leg, trunk and knee motions are also coupled with hip adduction and internal rotation (IR), and knee flexion and IR (84, 87, 171). Such coincident trunk/hip/knee motions have been termed "valgus collapse" (87), where knee valgus is synonymous with knee abduction.

Patterns of local knee joint kinematics are important because single- and combined-plane motions affect knee tissue forces. Anterior tibial displacement (ATD), knee abduction, and IR cause increased ACL stress and strain (102, 158). When each motion is superimposed on another for a combined motion pattern of simultaneous ATD, abduction, and IR, ACL stress and strain increase exponentially (102, 158). Because of the abduction component of the pattern, the medial collateral ligament (MCL) also experiences increased stress (54). When ACL and MCL stress increase, injury propensity increases as maximum strain is reached (187). Knee multi-plane combined motions such as those just described have been observed in 83.3% of netball noncontact ACL injuries (171) and 52.9% of basketball female noncontact ACL injuries (87).

Limiting unfavourable whole-body and local knee kinematics are desirable goals in netball noncontact knee injury preventions programs (IPP). Considering such goals are undertaken by a player (i.e. organism) executing a perceptual-motor task (i.e. skill) in a specific context (e.g. match) and environment (e.g. outdoor court), the situation and mechanism of netball noncontact knee STI can be viewed as a 'dynamical system' (2, 28) with multiple constraints (Table 1 and 2) interacting to influence the performance outcome (Figure 1). Practitioners should consider such constraints when planning knee IPPs.

4. Biomechanics of netball landings and high-risk events

Following on from knowledge of the situation/mechanics of noncontact knee STI, deeper understanding of a sport's kinetic and kinematic profile contributes to more thorough insights into its biomechanical demands (i.e. needs-analysis (45)) and specific 'high-risk' events containing potential for injury. Aligning with the biomechanical characteristics/variables popular in netball literature, this section will examine peak VGRF, time-to-peak VGRF (TTPVGRF), peak braking force (BF), and time-to-peak BF (TTPBF). Knee kinetics (moments) and kinematics (angles/displacements) will also be considered.

The peak VGRF is relevant because it represents foot-ground impact forces contributing to the magnitude of knee compression/shear/rotation forces (57, 139). In netball heel-strike or forefoot-strike SLLs after catching a pass, mean VGRFs were 5.3-5.7BW (165). For horizontal SLLs, mean VGRFs were 3.4BW (68). In SLLs and double-leg landings (DLL) after catching a pass, mean VGRFs were 3.5-5.7BW (133). For female basketball, mean VGRFs were 2.6-2.7BW for jump-shot-landings (36) and 2.2-2.3BW for rebound-jump-landings (85). In female volleyball, mean VGRFs were 1.6-2.1BW for block-jump-landings (72, 189) and 1.7-4.2BW for spike-jump-landings (5, 26). Therefore, netball-specific landings generate higher VGRFs than landings frequently performed by females in other court-sports.

The TTPVGRF is important because shorter TTPVGRFs represent higher rate-of-loading of musculoskeletal tissues (163) which present significant challenges for the neuromuscular system relative to attenuating harmful forces away from ligament/cartilage/bone (12, 127, 183). In netball, mean TTPVGRFs were 31.2ms and 30.6ms for heel-strike and forefoot-strike SLLs after catching a pass, respectively (165), 42.1-43.7ms for SLLs after catching a pass (77, 139), and 48.8ms for DLLs after catching a pass (133). For others, mean TTPVGRFs were 47.8ms for single-leg-drop-jumps in female soccer players (98) and 46.0ms for single-leg-drop-landings in predominantly female basketball players (131). Therefore, mean TTPVGRFs are consistently shorter for netball-specific SLLs than for other females' non-sport-specific SLLs.

The BF refers to horizontal ground reaction forces (HGRF) which push athletes posteriorly when landing with anteriorly-directed momentum (42). Peak BFs are relevant in netball for similar reasons as VGRFs and because the footwork-rule requires players to stop suddenly by reducing forward momentum rapidly (163, 165, 170). In netball, mean BFs were 4.5-4.6BW for SLLs after catching a pass (166), 3.3BW and 2.0BW for heel and forefoot SLLs after catching a pass (165), and 1.7BW for DLLs after catching a pass (133). For female basketball, mean BFs were 0.3-0.5BW for jump-shot-landings (36) and 1.3BW for run-rapid-stops (130). For female volleyball, mean BFs were 1.7BW for spike-jump-landings (26). Compared to females executing sport-specific landings in other court-sports, netball-specific SLLs generate higher BFs.

The TTPBF is important for identical reasons as the TTPVGRF. In netball heel-strike or forefoot-strike SLLs after catching a pass, mean TTPBFs were 23.9ms and 30.5ms, respectively (165). For SLLs and DLLs, mean TTPBFs were 26.4-44.7ms (133, 167). For other agility-sports, SLL/DLL TTPBFs have not been reported. In netball, mean TTPBFs appear short enough to elicit high tissue rate-of-loading (133, 163).

External and internal moments come from *outside* (e.g. VGRF) and *inside* (e.g. muscles) the body, respectively, and tend to cause joint rotation (57, 139). Peak external moments are important because they estimate forces experienced by soft tissues (e.g. ligaments) (57, 139), giving insight into the magnitude of moments that may injure such tissues. For a netball-specific SLLs, the knee mean *internal* adduction moment was near 0.4Nm/kg (170) and mean *internal* external rotation (ER) moment was near 0.1Nm/kg (178). External and internal moments balance each other, being equal and opposite in magnitude and direction, respectively (5, 57, 139). Therefore, a knee *internal* adduction moment of 0.4Nm/kg balances an *external* abduction moment of the same size and a knee *internal* ER moment of 0.1Nm/kg balances an *external* IR moment of the same size. For double-leg counter-movement jumps, netball players demonstrated knee mean *internal* moments for adduction and ER of 0.4Nm/kg and 0.2Nm/kg, respectively (160). In volleyball single-leg-spike-jump-landings, females demonstrated knee mean *internal* moments for adduction and ER of 0.2-0.5Nm/kg and 0.1-0.3Nm/kg, respectively (5). For basketball double-leg-rebound-jump-landings, females demonstrated knee mean *external* abduction moments of 0.2Nm/kg and *external* IR moments of 0.3Nm/kg (185). Comparatively, netball-specific SLLs result in relatively high knee peak *external* abduction moments.

Knowledge of knee kinematics (angles/displacements) gives further insight into biomechanical demands of landing tasks. Small sagittal-plane joint displacements are associated with ‘stiff’/‘abrupt’ landings, whereas large joint displacements are associated with ‘soft’/‘yielding’ landings (32, 153, 191). As for short TTPVGRFs, stiff landings elicit higher tissue loads and rate-of-loading than soft landings (32, 90, 153). For netball-specific SLLs, initial contact (IC (instant-of-touchdown)) mean knee flexion was 18.3° and at instant-of-peak-VGRF was 27.0° (24). In other netball-specific SLLs, IC mean knee flexion was near 15° and at 25% stance-phase was near 45° (170), and IC mean knee flexion was 16.3° and stance-phase mean flexion was 60.3° (159). For counter-movement-jump-landings, netball players exhibited IC and mean knee flexion of 21.1° and 85.2°, respectively (160). In female basketball, rebound-jump-landings demonstrated mean knee flexion displacement of near 75.0° (185). For female volleyball, block-jump-landings showed respective IC and peak knee flexion of 11.1-13.5° and 63.1-69.6° (110). Netball-specific SLLs display characteristics associated with stiff landings because of relatively small knee flexion displacements. Considering netball knee frontal plane kinematics, mean abduction angles were near 1.0-5.2° for SLLs (159, 170), 8.6° for DLLs (159), and 12.1° for counter-movement-jump-landings (160). For female basketball, mean knee abduction was 10.0° for rebound-jump-landings (185). In female volleyball, mean knee abduction was 5.0-7.7° for single-leg-spike-jump-landings (6) and 6.3-10.4° for block-jump-landings (72, 110). Mean peak knee abduction angles in netball players appear comparable to those in other female court-sports.

Based on data presented here, high VGRFs, short TTPVGRFs, high BFs, high knee external abduction moments, and small knee flexion displacements are characteristic of netball SLLs/DLLs. Decreased lower-limb flexion displacement during landings is associated with increased VGRFs (1, 94, 143), increased knee abduction moments (1, 143), and increased ACL forces (90). Increased VGRFs are associated with increased knee anterior shear forces (155, 188). Increased knee abduction moments are associated with increased ACL and MCL loads (102, 158). Higher rates-of-loading of knee ligaments predispose tissue failure more than lower rates-of-loading (128). Increased trunk lateral flexion (31) and rotation (25) towards a support-leg during SLLs/DLLs is associated with increased knee abduction moments and angles. High VGRFs, low peak knee flexion angles, and high knee external abduction moments are prospectively linked to noncontact ACL injuries in female athletes (64, 95). Thus, netball SLLs/DLLs contain high-risk biomechanical features that predispose noncontact knee STI. Features identified from laboratory-based research and known injury mechanisms derived from real-world observations input to the design of biomechanically-informed netball-specific knee IPPs.

5. Netball noncontact knee injury prevention preparticipation screening

Injury prevention screening aims to identify characteristics increasing athletes' likelihood of sustaining injury (179). Such characteristics are termed 'risk factors' (144). Risk factors are inside (intrinsic) or outside (extrinsic) the athlete (121) (Figure 2). Risk factors are nonmodifiable (e.g. age) and modifiable (e.g. muscle strength) according to potential effects of conservative interventions (37). Screening for the presence/absence of intrinsic risk factors relates to identifying athletes predisposed to injury (109) (Figure 2). When predisposed athletes enter situations containing extrinsic risk factors they become susceptible to injury (109) (Figure 2). Because little netball-specific screening research has been published, design of netball-specific screening procedures draws from related studies examining intrinsic, modifiable risk factors.

The ankle is a significant component in the lower-limb kinetic chain (137). In double-leg-drop-jumps, straight-knee ankle dorsiflexion range-of-motion measured with a goniometer negatively correlates with landing VGRFs, knee external abduction moments, and knee abduction displacements, and positively correlates with knee flexion displacements (47, 100). For double-leg-drop-landings, bent-knee ankle dorsiflexion range-of-motion measured with the weightbearing-lunge-test positively correlates with knee flexion displacements (71). Screening ankle dorsiflexion range-of-motion with goniometry or weightbearing-lunge-tests may, therefore, be useful for identifying netball players predisposed to sub-optimal landing biomechanics.

Outside 3D motion analysis, lower-limb internal moment generating ability is inferred using strength tests (35). For single-leg-drop-landings, isometric hip abduction and ER strength measured with a handheld dynamometer (HHD) negatively correlates with VGRFs, knee external abduction moments, knee anterior shear forces, and knee abduction angles (92, 173). For single-leg-drop-vertical-jumps, single-leg squat (SLS) strength measured with a barbell and isometric knee flexion strength measured with an isokinetic dynamometer (IKD) negatively correlates with knee abduction and IR angles (104). In prospective work, low lower-limb strength measured with one-repetition-maximum (1RM) barbell back-squats was associated with higher odds for traumatic knee injuries (149). In other prospective and case-control work, low isometric hip abduction and ER strength measured with an HHD (82) and low knee flexion strength measured with an IKD (114) were associated with experiencing noncontact knee injury. Collectively, the studies cited here indicate increased hip and knee muscle strength is linked to more desirable landing biomechanics and decreased noncontact knee STI risk. Screening hip and knee muscle strength using double-/single-leg strength tests may, therefore, be useful for identifying netball players predisposed to sub-optimal landing biomechanics and risk for knee STI. Given that quadriceps and gastrocnemius/soleus control knee flexion and ankle dorsiflexion, respectively, and dissipation of landing impact forces (191), screening of knee extensor (22) and ankle plantarflexor muscle strength (14, 76) may be prudent. However, IKDs and HHDs can be expensive and often inaccessible to community-based practitioners (22). Alternatively, leg press, knee flexion, and knee extension resistance machines are more readily available (22). Subsequently, single-leg 1RM strength tests can be performed with netball players in local communities (17, 22). Combining free-weight and resistance machine procedures for strength testing may be most thorough.

Trunk position/motion can influence knee biomechanics (25, 31, 63). In horizontal-jump-cuts, isokinetic trunk rotation strength negatively correlates with knee abduction displacement (80). For SLS, isometric side-bridge strength measured with an HHD (120) and strength-endurance measured via holding-time (186) negatively correlates with knee abduction angles. No prospective work has examined the association between trunk muscle strength and future noncontact knee STI. However, one prospective study demonstrated high trunk displacements following laterally-directed perturbations linked to higher odds for experiencing noncontact ACL injury (190). Subsequently, screening trunk lateral flexor muscle strength may provide useful data identifying netball players predisposed to sub-optimal lower-limb biomechanics and risk for knee STI.

Balance refers to maintaining the body's center-of-mass and center-of-pressure within its base-of-support (99). In single-leg-drop-landings, eyes-open single-leg balance (SLB) defined by force-plate center-of-pressure excursion positively correlated with knee external abduction moments (34). In prospective studies, poor eyes-open and eyes-closed SLB measured with a computer associated with increased ankle sprain incidence (106). Poor eyes-open single-leg balance measured with three (anterior/posteromedial/posterolateral) of the six directions of the Star Excursion Balance Test (SEBT) prospectively related to increased odds for lower-limb injury including knee sprains (142). Poor eyes-open SLB measured with a computer prospectively linked to increased ACL injury frequency (151). Screening SLB with procedures such as timed performance and abbreviated SEBT (20, 21, 142) may, therefore, have utility for identifying netball players predisposed to sub-optimal landing biomechanics and risk for knee STI.

Movement screening assesses kinematic patterns relative to the biomechanics of injury mechanisms and high-risk events. Because 3D motion analysis is often not accessible to community-based practitioners, 2D procedures have been developed using commonly available video cameras. During SLLs/DLLs, 2D measurements of frontal plane knee kinematics are generally not related to concurrent 3D measurements (58, 111, 162). During SLS, however, 2D measurements of frontal plane knee kinematics are related to concurrent 3D measurements (56, 58, 152). For netball screening, a SLS is advocated because its knee biomechanics are related to those in netball-specific SLLs (51). If video cameras are not accessible, generic 'observational' DLL (e.g. Landing Error Scoring System (LESS)-Real Time (LESS-RT) (135)) and SLS (16, 59) movement screens have been developed. Generic DLL movement screens such as the LESS, however, are not related to netball-specific SLL biomechanics (48). One group reported reliability of the 'Netball Movement Screening Tool' (147) which contains 12 tasks relevant to knee injury risk (Table 3). In prospective research, trunk ipsilateral lateral flexion and knee abduction during single-leg drop-vertical-jumps measured with 2D motion analysis were linked to increased noncontact knee STI frequency (33), and poor (higher) LESS scores extracted from 2D motion analysis were associated with increased noncontact ACL injury frequency (136). Subsequently, 2D video analyses and observational movement screens may be useful for identifying netball players predisposed to sub-optimal landing biomechanics and risk for knee STI.

Lower-limb functional performance tests (FPT) include hop, leap, and jump tests (18). In sports medicine, single-leg FPTs (SL-FPT) isolate each lower-limb and expose unilateral deficits that can remain hidden in double-leg tasks (18, 116, 117). No published work has examined associations between SL-FPT variables and knee biomechanical characteristics derived from 3D motion analysis. In contrast, SL-FPTs are prospectively associated with noncontact lower-limb STI in agility-sport athletes. For the single-leg-hop-for-distance, athletes with a mean distance of ≤64% of height for either limb possessed increased thigh/knee injury risk (10). Also for the single-leg-hop-for-distance, side-to-side asymmetry of >10% was associated with noncontact ankle/foot trauma (11). Screening SL-FPTs may, therefore, be useful for identifying netball players predisposed to increased risk for knee STI. Recently, screening of community-level netball players using SL-FPTs revealed side-to-side absolute-asymmetries (Table 4, footnote) 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 (21). Given such proportions, netball knee injury prevention screening may benefit from using a selection of SL-FPTs.

Based on the research cited in this section, example netball-specific knee intrinsic risk factor screening tests are presented in Table 4. It may not be necessary to perform all tests and practitioners can decide for themselves which tests/variables are viable based on their local logistical constraints (e.g. equipment/personnel/finance/time availability).

6. Netball noncontact knee injury prevention training programs

When the situation and mechanism of injury are understood, the biomechanics of high-risk events are familiar, and intrinsic risk factors are identified, the design of focused IPPs can commence (43, 177). Multiple factors are involved in traumatic injuries (8, 140) and multiple factors may need consideration following screening (Table 4). Different modes of exercise intervention, therefore, contribute to netball noncontact knee IPPs.

Strength training (ST) refers to exercise aimed at improving muscles' ability to generate force (23, 172). Application of forces to the body can also beneficially modify skeletal tissues. Animal (129, 175) and human (112) trials show controlled loading via bodyweight/external loads enhances the mechanical properties (load-to-failure/stiffness) of knee ligaments. Thus, the deliberate use of ST to apply controlled loads to modify tissues' mechanical characteristics is termed "tissue conditioning" (19). Further, ST can modify high-risk biomechanical characteristics and reduce injury frequency. Strength training-focused programs for the trunk and lower-limbs resulted in decreased VGRFs, increased knee flexion angles, and decreased knee abduction angles during SLLs in females (3, 60, 93, 105). Meta-analyses demonstrate multi-modal training programs including substantial ST components are more effective at reducing female ACL injury incidence than those that do not (172). Strength training, therefore, is an essential component in netball noncontact knee IPPs.

Balance-focused programs for the trunk and lower-limbs have demonstrated decreased VGRFs, increased knee flexion angles, and decreased knee abduction angles during SLLs in female athletes (115, 118). Balance training-focused programs have also reduced ACL injury incidence in male soccer (13). Balance training, therefore, is an important component in noncontact knee IPPs. Remembering 50% of netball ACL injuries result from indirect contact with opponents (171), balance drills should progress to include jostling/pushing with a partner (123, 125).

Plyometric-focused programs resulted in decreased VGRFs, increased knee flexion angles, decreased knee external abduction moments, and decreased knee abduction angles during SLLs/DLLs in females (60, 75, 118, 180). Plyometric-focused programs with higher volumes of plyometric versus ST exercise resulted in decreased incidence of female noncontact ACL injuries (62). Meta-analyses indicate multi-modal IPPs including substantial plyometrics components are more effective at reducing noncontact ACL injury incidence than those that do not (61, 119, 148, 182). Subsequently, plyometric training is another essential component in netball noncontact knee IPPs. Multiple SLL/DLL/split-landing types occur in netball (52, 70, 91), all of which are influenced by extrinsic risk factors and opponents' behaviour (Figure 2). Therefore, when incorporating plyometric training to improve netball landing biomechanics, it is vital to coach fundamental landing principles that transfer to diverse practice/match situations (113). Suggested principles are described in Table 5 and illustrated in Figure 3-4. Although asphalt surfaces should be avoided for plyometric training (66), given that netball is played on outdoor asphalt courts (67, 78, 141), and most knee injuries occur on asphalt (67, 78, 141), practitioners may wish to progress plyometric training from yielding surfaces to asphalt to fulfil specific-adaptation-to-imposed-demands (SAID) principles (81). Remembering again 50% of netball ACL injuries result from indirect contact with opponents

(171), plyometric drills should also progress to include mid-air shoulder-trunk bumping/collision with a partner (123, 125).

Core training can modify high-risk biomechanical characteristics. One study (3) reported core-focused training reduced VGRFs during DLLs in females. No prospective study has examined the effect of core-focused training on noncontact knee STI incidence. However, meta-analyses report multi-modal training programs including substantial core training components are more effective at reducing ACL injury incidence than those that do not (172). Core training, consequently, is important in noncontact knee IPPs.

Collectively, multi-modal strength, balance, plyometric, and core training programs appear most effective at reducing female noncontact knee STIs (61, 119, 148, 182). Multi-modal programs are effective when performed preseason or in-season (148), delivered as standalone sessions within periodized training plans (62) or as warm-ups within technical training sessions (38, 88, 101, 132). Multi-modal programs are commonly generic with identical exercises for all players (38, 62, 101, 132) rather than being individualized with targeted interventions according to preparticipation screening findings. Multi-modal netball generic warm-up programs have been developed in Australia (The KNEE Program) (123) and New Zealand (NetballSmart) (125) but their effectiveness for preventing noncontact knee STIs remains unpublished. Although generic programs are popular from logistical perspectives, individualized interventions are also advocated according to a single player's unique needs (20, 21, 150, 179). Optimal strategies for netball players may be to undertake individualized sessions containing targeted interventions at certain times in a microcycle and then also undertake team-level technical sessions that contain generic warm-ups at other times in a microcycle (39). Given the majority of netball landings are SLLs (70, 91), the majority of exercises should be single-leg exercises to facilitate unilateral intrinsic risk factor resolution. Example netball preseason training for community-level players is illustrated in Tables 6-8.

When designing training session content, progression to more ecologically-valid exercises/drills should occur. Perception-action coupling includes operations *within* the central nervous system relative to translating at-that-moment-in-time sensory information to experience-based meaning (perception) followed by skilled movement congruent with contextual/environmental demands (action) (2, 28, 146) (Figure 1). In netball, performance occurs in open-skilled contexts where skills are externally-paced relative to unpredictable environmental constraints (181) (e.g. opponents' behaviour (Figure 1)). Such constraints present significant problem-solving/decision-making challenges which can result in information-overload, unsuccessful skill execution, and injury (Figure 1). For landing tasks in closed-skill contexts, superimposed problem-solving (27, 79, 145) and stimulus-response reaction-time (9, 154, 169) tasks alter landing biomechanics such that knee kinetics/kinematics become similar to those in noncontact knee STI events. Therefore, when designing netball noncontact knee IPPs, practitioners should progress exercises/drills to include cognitive-loading/reaction-time elements. Because netball injuries can occur in team training sessions (78), it is prudent to intervene so that intrinsic risk factors are prioritized before progressing to closed-/open-skilled practices exposing the player to extrinsic risk factors (Figure 5).

Practitioners must also ensure players are physiologically prepared for match-play. Players perform many anaerobic activities (e.g. jumping/sprinting) during match-play (49, 164) which contain critical moments deciding match outcomes (49, 50, 174). Therefore, energy-system training including high-intensity, short-duration running is needed to mimic match-specific anaerobic activities. Adequate rest periods allow the alactic acid system to recover and work:rest ratios of 1:5 are recommended (49, 174). The intermittent nature of netball means that players should also have high-level aerobic fitness to endure a one-hour match (15, 174). Subsequently, energy-system training including low-/moderate-intensity long-duration running is also needed to expedite recovery from anaerobic activities (15, 174). Example netball preseason energy-system training for community-level players is illustrated in Tables 9-10.

7. Summary

Netball is a team sport played worldwide. Knee injuries are common, with match-play noncontact knee STI being most frequent due to knee abduction/valgus collapse during landing tasks. High-risk landing events that contain the potential for noncontact knee STI are common in netball. Studies reveal joint mobility, muscle strength, balance, movement pattern, and SL-FPT characteristics link to high-risk landing biomechanics and actual noncontact knee injury frequency in females. Such characteristics should be considered in netball-specific noncontact knee injury preparticipation screening. Strength, balance, movement, and plyometric training are capable of beneficially modifying high-risk landing biomechanics and reducing noncontact knee STI frequency in females. Such training methods should be included in netball-specific multi-modal noncontact knee IPPs. This paper provides insight into noncontact knee injury-related aspects of netball. Such insight helps practitioners plan targeted interventions contributing to netball noncontact knee STI prevention that promote players' safe participation across the lifespan.

Table Legends and Footnotes

Table 1. Example factors in analysing and understanding a knee injury event*

*Modified from references: 7,86,171

Table 2. Contact, indirect contact, and noncontact nature of knee injury*

*Modified from references: 87,103,171

Table 3. Components and tests in the Netball Movement Screening Tool*

*from reference 147: see this citation for scoring information
BW = bodyweight; ASLR = active straight-leg raise

Table 4. Example netball-specific noncontact knee injury prevention preparticipation screening tests*

*all single-leg tests are performed for both right and left sides.
DF = dorsiflexion; ROM = range-of-motion; ° = degrees; cm = centimeters; 1RM = one repetition maximum;
%BW = percentage of bodyweight = (weight lifted (kg) ÷ bodyweight (kg)) × 100;
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);

HHD = handheld dynamometer; ER = external rotation; s = seconds; 2D = two dimensional; LESS-RT = Landing Error Scoring System-Real Time; QASLS = Qualitative Analysis of Single-Leg Squat;
%LL = percentage of leg-length = (distance hopped (cm) ÷ leg-length (cm)) × 100;
%H = percentage of standing height = (distance hopped (cm) ÷ standing height (cm)) × 100.
** = see Related Study citation for scoring system.

Table 5. Suggested fundamental double-leg and single-leg alignment/landing principles for plyometric training*

*Modified from reference: 113

Table 6. Example preseason single-week microcycle for community-level netball players

Table 7. Example preseason individualized multi-modal exercise training session*

*Load for strength training exercises will be individualized relative to the desired number of repetitions for a set
**single-leg exercises are repeated on right and left sides
DL= double-leg; BW=bodyweight; SL = single-leg

Table 8. Example preseason generic multi-modal 15-minute warm-up for all players prior to a team-level netball skills/tactics training session

Table 9. Example preseason single-session aerobic energy system training program

Table 10. Example preseason single-session anaerobic energy systems training program

Figure Legends

Figure 1. Example netball dynamical system model with possible constraints and outcomes (modified from 28)

Figure 2. Example multifactorial model of netball noncontact knee soft tissue injury etiology (modified from 109)

Figure 3. Suggested fundamental double-leg landing alignment (modified from 113)

Figure 4. Suggested fundamental single-leg landing alignment (modified from 113)

Figure 5. Example intervention progression for intrinsic and extrinsic risk factors for netball noncontact knee soft tissue injury

References

1. Ali N, Rouhi G, and Robertson G. Gender, Vertical Height and Horizontal Distance Effects on Single-Leg Landing Kinematics: Implications for Risk of non-contact ACL Injury. *Journal of Human Kinetics* 37: 27-38, 2013.
2. Anson G, Elliott D, and Davids K. Information Processing and Constraints-based Views of Skill Acquisition: Divergent or Complementary. *Motor Control* 9: 217-241, 2005.
3. Araujo S, Cohen D, and Hayes L. Six weeks of core stability training improves landing kinetics among female capoeira athletes: a pilot study. *Journal of Human Kinetics* 45: 27-37, 2015.
4. Attenborough AS, Sinclair PJ, Sharp T, Greene A, Stuelcken M, Smith RM, and Hiller CE. A snapshot of chronic ankle instability in a cohort of netball players. *Journal of Science and Medicine in Sport* 19: 379-383, 2016.
5. Avedesian JM, Judge LW, Wang H, and Dicken DC. Kinetic Analysis of Unilateral Landings in Female Volleyball Players after a Dynamic and Combined Dynamic-Static Warm-up. *Journal of Strength and Conditioning Research* 33: 1524-1533, 2019.
6. Avedesian JM, Judge LW, Wang H, and Dickin DC. The biomechanical effect of warm-up stretching strategies on landing mechanics in female volleyball athletes. *Sports Biomechanics*: 1-14, 2018.
7. Bahr R and Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *British Journal of Sports Medicine* 39: 324-329, 2005.

8. Barss P, Smith G, Baker S, and Mohan D. *Injury Prevention: An International Perspective Epidemiology, Surveillance, and Policy.* 1998.
9. Brown TN, Palmieri-Smith RM, and McLean SG. Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: implications for anterior cruciate ligament injury. *British Journal of Sports Medicine* 43: 1049-1056, 2009.
10. Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, Mattocks A, and Rauh MJ. Preseason functional test scores are associated with future sports injury in female collegiate athletes. *The Journal of Strength & Conditioning Research* 32: 1692-1701, 2018.
11. Brumitt J, Heiderscheit BC, Manske RC, Niemuth PE, and Rauh MJ. Lower extremity functional tests and risk of injury in division iii collegiate athletes. *International Journal of Sports Physical Therapy* 8: 216-227, 2013.
12. Buckwalter JA. Sports, Joint Injury, and Posttraumatic Osteoarthritis. *Journal of Orthopedic Sports Physical Therapy* 33: 578-588, 2003.
13. Caraffa A, Cerulli G, Projetti M, Aisa G, and Rizzo A. Prevention of anterior cruciate ligament injuries in soccer. *Knee Surgery, Sports Traumatology, Arthroscopy* 4: 19-21, 1996.
14. Cen XZ, Liang ZQ, Gao ZX, Lian WL, and Wang ZM. The Influence of the Improvement of Calf Strength on Barefoot Loading. Presented at Journal of Biomimetics, Biomaterials and Biomedical Engineering, 2019.
15. Chandler PT, Pinder SJ, Curran JD, and Gabbett TJ. Physical demands of training and competition in collegiate netball players. *Journal of Strength and Conditioning Research* 28: 2732-2737, 2014.
16. Chmielewski TL, Hodges MJ, Horodyski M, Bishop MD, Conrad BP, and Tillman SM. Investigation of clinician agreement in evaluating movement quality during unilateral lower extremity functional tasks: a comparison of 2 rating methods. *Journal of Orthopaedic and Sports Physical Therapy* 37: 122-129, 2007.
17. Clark N, Gumbrell C, Rana S, and Morrissey MC. The Relationship Between Vertical Hop Performance and Isotonic Open and Closed Kinetic Chain Muscle Strength of the Lower Limb. Presented at British Association of Sport and Exercise Sciences Annual Conference, Liverpool, England, 2001.
18. Clark NC. Functional performance testing following knee ligament injury. *Physical Therapy in Sport* 2: 91-105, 2001.
19. Clark NC. The role of physiotherapy in rehabilitation of soft tissue injuries of the knee. *Orthopaedics and Trauma* 29: 48-56, 2015.
20. Clark NC and Clacher LH. Lower-limb motor-performance asymmetries in English community-level female field hockey players: Implications for knee and ankle injury prevention. *Physical Therapy in Sport* 43: 43-51, 2020.
21. Clark NC and Mullally EM. Prevalence and magnitude of preseason clinically-significant single-leg balance and hop test asymmetries in an English adult netball club. *Physical Therapy in Sport* 40: 44-52, 2019.
22. Clark NC, Reilly LJ, and 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. *Physical Therapy in Sport* 40: 128-136, 2019.
23. Clark NC, Röijezon U, and Treleaven J. Proprioception in musculoskeletal rehabilitation. Part 2: Clinical assessment and intervention. *Manual Therapy* 20: 378-387, 2015.
24. Cowling EJ and Steele JR. Is lower limb muscle synchrony during landing affected by gender? Implications for variations in ACL injury rates. *Journal of Electromyography and Kinesiology* 11: 263-268, 2001.
25. Critchley ML, Davis DJ, Keener MM, Layer JS, Wilson MA, Zhu Q, and Dai B. The effects of mid-flight whole-body and trunk rotation on landing mechanics: implications for anterior cruciate ligament injuries. *Sports Biomechanics*: 1-17, 2019.

26. Cronin JB, Bressel E, and Finn L. Augmented Feedback Reduces Ground Reaction Forces in the Landing Phase of the Volleyball Spike Jump. *Journal of Sport Rehabilitation* 17: 148-159, 2008.
27. Dai B, Cook RF, Meyer EA, Sciascia Y, Hinshaw TJ, Wang C, and Zhu Q. The effect of a secondary cognitive task on landing mechanics and jump performance. *Sports Biomechanics* 17: 192-205, 2018.
28. Davids K, Glazier P, Araujo D, and Bartlett R. Movement Systems as Dynamical Systems. The Functional Role of Variability and its Implications for Sports Medicine. *Sports Medicine* 33: 245-260, 2003.
29. Davis DJ, Hinshaw TJ, Critchley ML, and Dai B. Mid-flight trunk flexion and extension altered segment and lower extremity joint movements and subsequent landing mechanics. *Journal of Science and Medicine in Sport* 22: 955-961, 2019.
30. de Loes M, Dahlstedt LJ, and Thomee R. A 7-year study on risks and costs of knee injuries in male and female youth participants in 12 sports. *Scandanavian Journal of Medicine and Science in Sports* 10: 90-97, 2000.
31. Dempsey AR, Elliott BC, Munro BJ, Steele JR, and Lloyd DG. Whole body kinematics and knee moments that occur during an overhead catch and landing task in sport. *Clinical Biomechanics* 27: 466-474, 2012.
32. Devita P and Skelly PA. Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise* 24: 108-115, 1992.
33. Dingenen B, Malfait B, Nijs S, Peers KH, Vereecken S, Verschueren SM, and Staes FF. Can two-dimensional video analysis during single-leg drop vertical jumps help identify non-contact knee injury risk? A one-year prospective study. *Clinical Biomechanics* 30: 781-787, 2015.
34. Durall CJ, Kernozek TW, Kersten M, Nitz M, Setz J, and Beck S. Associations between single-leg postural control and drop-landing mechanics in healthy women. *Journal of Sport Rehabilitation* 20: 406-418, 2011.
35. Dvir Z. *Isokinetics: Muscle Testing, Interpretation, and Clinical Applications.* Churchill Livingstone, 2004.
36. Elliott B and White E. A kinematic comparison of the male and female two-point and three-point jump shots in basketball. *The Australian Journal of Science and Medicine in Sport* 21: 7-11, 1989.
37. Emery CA. Risk Factors for Injury in Child and Adolescent Sport: A Systematic Review of the Literature. *Clinical Journal of Sports Medicine* 13: 256-268, 2003.
38. Emery CA and Meeuwisse WH. The effectiveness of a neuromuscular prevention strategy to reduce injuries in youth soccer: a cluster-randomised controlled trial. *British Journal of Sports Medicine* 44: 555-562, 2010.
39. Emery CA, Rose MS, McAllister JR, and Meeuwisse WH. A Prevention Strategy to Reduce the Incidence of Injury in High School Basketball: A Cluster Randomized Controlled Trial. *Clinical Journal of Sport Medicine* 17: 17-24, 2007.
40. https://www.englandnetball.co.uk/coachblog/top-10-10th-injury-prevention/. Accessed June 16/2020.
41. England Netball. England Netball Membership Statistics. Hertfordshire, England, 2017.
42. Fietzer AL, Chang YJ, and Kulig K. Dancers with patellar tendinopathy exhibit higher vertical and braking ground reaction forces during landing. *Journal of Sports Science* 30: 1157-1163, 2012.
43. Finch C. A new framework for research leading to sports injury prevention. *Journal of Science and Medicine in Sport* 9: 3-9, 2006.
44. Finch C and Cassell E. The public health impact of injury during sport and active recreation. *Journal of Science and Medicine in Sport* 9: 490-497, 2006.
45. Fleck SJ and Kraemer W. *Designing Resistance Training Programs.* Human Kinetics, 2014.

46. Flood L and Harrison JE. Epidemiology of basketball and netball injuries that resulted in hospital admission in Australia, 2000-2004. *Medical Journal of Australia* 190: 87-90, 2009.
47. Fong CM, Blackburn JT, Norcross MF, McGrath M, and Padua DA. Ankle-dorsiflexion range of motion and landing biomechanics. *Journal of Athletic Training* 46: 5-10, 2011.
48. Fox A, Bonacci J, McLean S, and Saunders N. Efficacy of ACL injury risk screening methods in identifying high-risk landing patterns during a sport-specific task. *Scandinavian Journal of Medicine and Science in Sports* 27: 525-534, 2017.
49. Fox A, Spittle M, Otago L, and Saunders N. Activity profiles of the Australian female netball team players during international competition: implications for training practice. *Journal of Sports Science* 31: 1588-1595, 2013.
50. Fox A, Spittle M, Otago L, and Saunders N. Offensive Agility Techniques Performed during International Netball Competition. *International Journal of Sports Science & Coaching* 9: 543-552, 2014.
51. Fox AS, Bonacci J, and 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*: 1-17, 2018.
52. Fox SA, Spittle M, Otago L, and Saunders N. Descriptive analysis of landings during international netball competition: Enhancing ecological validity of laboratory testing environments. *International Journal of Performance Analysis in Sport* 13: 690-702, 2013.
53. Freedman KB, Glasgow MT, Glasgow SG, and Bernstein J. Anterior Cruciate Ligament Injury and Reconstruction Among University Students. *Clinical Orthopaedics and Related Research* 356: 208-212, 1998.
54. Gardiner JC, Weiss JA, and Rosenberg TD. Strain in the Human Medial Collateral Ligament During Valgus Loading of the Knee. *Clinical Orthopaedics and Related Research* 391: 266-274, 2001.
55. Genoese F, Baez S, and Hoch JM. The Association of Fear-Avoidance Beliefs and Self-Reported Knee Function in Patients With a Knee Injury: A Critically Appraised Topic. *International Journal of Athletic Therapy and Training* 23: 187-191, 2018.
56. Gwynne CR and Curran SA. Quantifying frontal plane knee motion during single limb squats: Reliability and validity of 2-dimensional measures. *International Journal of Sports Physical Therapy* 9: 898-906, 2014.
57. Hall S. *Basic Biomechanics.* McGraw-Hill Higher Education, 2014.
58. Herrington L, Alenezi F, Alzhrani M, Alrayani H, and Jones R. The reliability and criterion validity of 2D video assessment of single leg squat and hop landing. *Journal of Electromyography and Kinesiology* 34: 80-85, 2017.
59. Herrington L and Munro A. A preliminary investigation to establish the criterion validity of a qualitative scoring system of limb alignment during single-leg squat and landing. *Journal of Exercise, Sports and Orthopedics* 1: 1-6, 2014.
60. Herrington L, Munro A, and Comfort P. A preliminary study into the effect of jumping-landing training and strength training on frontal plane projection angle. *Manual Therapy* 20: 680-685, 2015.
61. Hewett TE, Ford KR, and Myer GD. Anterior cruciate ligament injuries in female athletes: Part 2, a meta-analysis of neuromuscular interventions aimed at injury prevention. *The American Journal of Sports Medicine* 34: 490-498, 2006.
62. Hewett TE, Lindenfeld TN, Riccobene JV, and Noyes FR. The effect of neuromuscular training on the incidence of knee injury in female athletes. *The American Journal of Sports Medicine* 27: 699-706, 1999.
63. Hewett TE and Myer GD. The mechanistic connection between the trunk, hip, knee, and anterior cruciate ligament injury. *Exercise and Sport Sciences Reviews* 39: 161-166, 2011.
64. Hewett TE, Myer GD, Ford KR, Heidt RS, Jr., Colosimo AJ, McLean SG, van den Bogert AJ, Paterno MV, and Succop P. Biomechanical measures of neuromuscular control and valgus

loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *The American Journal of Sports Medicine* 33: 492-501, 2005.
65. Hewett TE, Torg JS, and Boden BP. Video analysis of trunk and knee motion during non-contact anterior cruciate ligament injury in female athletes: lateral trunk and knee abduction motion are combined components of the injury mechanism. *British Journal of Sports Medicine* 43: 417-422, 2009.
66. Holcomb WR, Kleiner DM, and Chu DA. Plyometrics: Considerations for Safe and Effective Training. *Strength and Conditioning* 20: 36-41, 1998.
67. Hopper D. A Survey of Netball Injuries and Conditions Related to These Injuries. *Australian Journal of Physiotherapy* 32: 231-239, 1986.
68. Hopper D and Elliott B. Lower limb and back injury patterns of elite netball players. *Sports Medicine* 16: 148-162, 1993.
69. Hopper D, Elliott B, and Lalor J. A descriptive epidemiology of netball injuries during competition: a five year study. *British Journal of Sports Medicine* 29: 223-228, 1995.
70. Hopper D, Kai Lo S, Kirkham C, and Elliott B. Landing patterns in netball: analysis of an international game. *British Journal of Sports Medicine* 26: 101-106, 1992.
71. Howe LP, Bampouras TM, North J, and 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. *Human Movement Science* 64: 320-328, 2019.
72. Hughes G, Watkins J, and Owen N. The effects of opposition and gender on knee kinematics and ground reaction force during landing from volleyball block jumps. *Research Quarterly for Exercise and Sport* 81: 384-391, 2010.
73. International Netball Federation. Netball Rule Book. 2020.
74. http://netball.org/inside-inf/regions-members. Accessed Jan 13, 2020/.
75. Irmischer BS, Harris C, Pfeiffer RP, DeBeliso MA, Adams KJ, and Shea KG. Effects of a Knee Ligament Injury Prevention Exercise Program on Impact Forces in Women. *Journal of Strength and Conditioning Research* 18: 703-707, 2004.
76. Jamurtas AZ, Fatouros IG, Buckenmeyer P, Kokkinidis E, Taxildaris K, Kambas A, and Kyriazis G. Effects of plyometric exercise on muscle soreness and plasma creatine kinase levels and its comparison with eccentric and concentric exercise. *Journal of Strength and Conditioning Research* 14: 68-74, 2000.
77. Janssen KW, Orchard JW, Driscoll TR, and 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? *Scandanavian Journal of Medicine and Science in Sports* 22: 495-501, 2012.
78. Joseph C, Naughton G, and Antcliff A. Australian netball injuries in 2016: An overview of insurance data. *Journal of Science and Medicine in Sport* 22: 1304-1308, 2019.
79. Kajiwara M, Kanamori A, Kadone H, Endo Y, Kobayashi Y, Hyodo K, Takahashi T, Arai N, Taniguchi Y, Yoshioka T, and Yamazaki M. Knee biomechanics changes under dual task during single-leg drop landing. *Journal of Experimental Orthopaedics* 6: 1-6, 2019.
80. Keenan KA, Varnell MS, Sell TC, Abt JP, Lovelekar MT, and Lephart SM. Importance of Hip and Trunk on the Lower Extremity Balance and Motion. Presented at Journal of Athletic Training, 2015.
81. Kegerreis S. The Construction and Implementation of Functional Progressions as a Component of Athletic Rehabilitation. *Journal of Orthopaedic and Sports Physical Therapy* 5: 14-19, 1983.
82. Khayambashi K, Ghoddosi N, Straub RK, and Powers CM. Hip Muscle Strength Predicts Noncontact Anterior Cruciate Ligament Injury in Male and Female Athletes: A Prospective Study. *The American Journal of Sports Medicine* 44: 355-361, 2016.
83. Kirtley C. *Clinical gait analysis: theory and practice.* Elsevier Health Sciences, 2006.

84. Koga H, Nakamae A, Shima Y, Iwasa J, Myklebust G, Engebretsen L, Bahr R, and Krosshaug T. Mechanisms for noncontact anterior cruciate ligament injuries: knee joint kinematics in 10 injury situations from female team handball and basketball. *The American Journal of Sports Medicine* 38: 2218-2225, 2010.
85. Kondo H and Someya F. Changes in ground reaction force during a rebound-jump task after hip strength training for single-sided ankle dorsiflexion restriction. *The Journal of Physical Therapy Science* 28: 318-325, 2016.
86. Krosshaug T, Andersen TE, Olsen OE, Myklebust G, and Bahr R. Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities. *British Journal of Sports Medicine* 39: 330-339, 2005.
87. Krosshaug T, Nakamae A, Boden BP, Engebretsen L, Smith G, Slauterbeck JR, Hewett TE, and Bahr R. Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *The American Journal of Sports Medicine* 35: 359-367, 2007.
88. LaBella CR, Huxford MR, Grissom J, Kim K, Peng J, and Christoffel KK. Effect of Neuromuscular Warm-up on Injuries in Female Soccer and Basketball Athletes in Urban Public High Schools. Cluster Randomized Controlled Trial. *Archives of Pediatrics and Adolescent Medicine* 165: 1033-1040, 2011.
89. Langeveld E, Coetzee FF, and Holtzhausen LJ. Epidemiology of Injuries in Elite South African Netball Players. *South African Journal for Research in Sport* 34: 83-93, 2012.
90. Laughlin WA, Weinhandl JT, Kernozek TW, Cobb SC, Keenan KG, and O'Connor KM. The effects of single-leg landing technique on ACL loading. *Journal of Biomechanics* 44: 1845-1851, 2011.
91. Lavipour D. Development of a Netball Specific Dynamic Balance Assessment. 2009.
92. Lawrence RK, 3rd, Kernozek TW, Miller EJ, Torry MR, and Reuteman P. Influences of hip external rotation strength on knee mechanics during single-leg drop landings in females. *Clinical Biomechanics* 23: 806-813, 2008.
93. Lephart SM, Abt JP, Ferris CM, Sell TC, Nagai T, Myers JB, and Irrgang JJ. Neuromuscular and biomechanical characteristic changes in high school athletes: a plyometric versus basic resistance program. *British Journal of Sports Medicine* 39: 932-938, 2005.
94. Leppanen M, Pasanen K, Krosshaug T, Kannus P, Vasankari T, Kujala UM, Bahr R, Perttunen J, and Parkkari J. Sagittal Plane Hip, Knee, and Ankle Biomechanics and the Risk of Anterior Cruciate Ligament Injury: A Prospective Study. *Orthopedic Journal of Sports Medicine* 5: 2325967117745487, 2017.
95. Leppanen M, Pasanen K, Kujala UM, Vasankari T, Kannus P, Ayramo S, Krosshaug T, Bahr R, Avela J, Perttunen J, and Parkkari J. Stiff Landings Are Associated With Increased ACL Injury Risk in Young Female Basketball and Floorball Players. *The American Journal of Sports Medicine* 45: 386-393, 2017.
96. Lie MM, Risberg MA, Storheim K, Engebretsen L, and Oiestad BE. What's the rate of knee osteoarthritis 10 years after anterior cruciate ligament injury? An updated systematic review. *British Journal of Sports Medicine* 53: 1162-1167, 2019.
97. Lohmander LS, Englund PM, Dahl LL, and Roos EM. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *The American Journal of Sports Medicine* 35: 1756-1769, 2007.
98. Lyle MA, Valero-Cuevas FJ, Gregor RJ, and Powers CM. Control of dynamic foot-ground interactions in male and female soccer athletes: Females exhibit reduced dexterity and higher limb stiffness during landing. *Journal of Biomechanics* 47: 512-517, 2014.
99. Macpherson J and Horak F. Posture, in: *Principles of neural science*. E Kandel, J Schwartz, T Jessell, SAH Siegelbaum, eds. New York: McGraw-Hill, 2013, pp 935-959.
100. Malloy P, Morgan A, Meinerz C, Geiser C, and Kipp K. The association of dorsiflexion flexibility on knee kinematics and kinetics during a drop vertical jump in healthy female athletes. *Knee Surgery, Sports Traumatology, Arthroscopy* 23: 3550-3555, 2015.

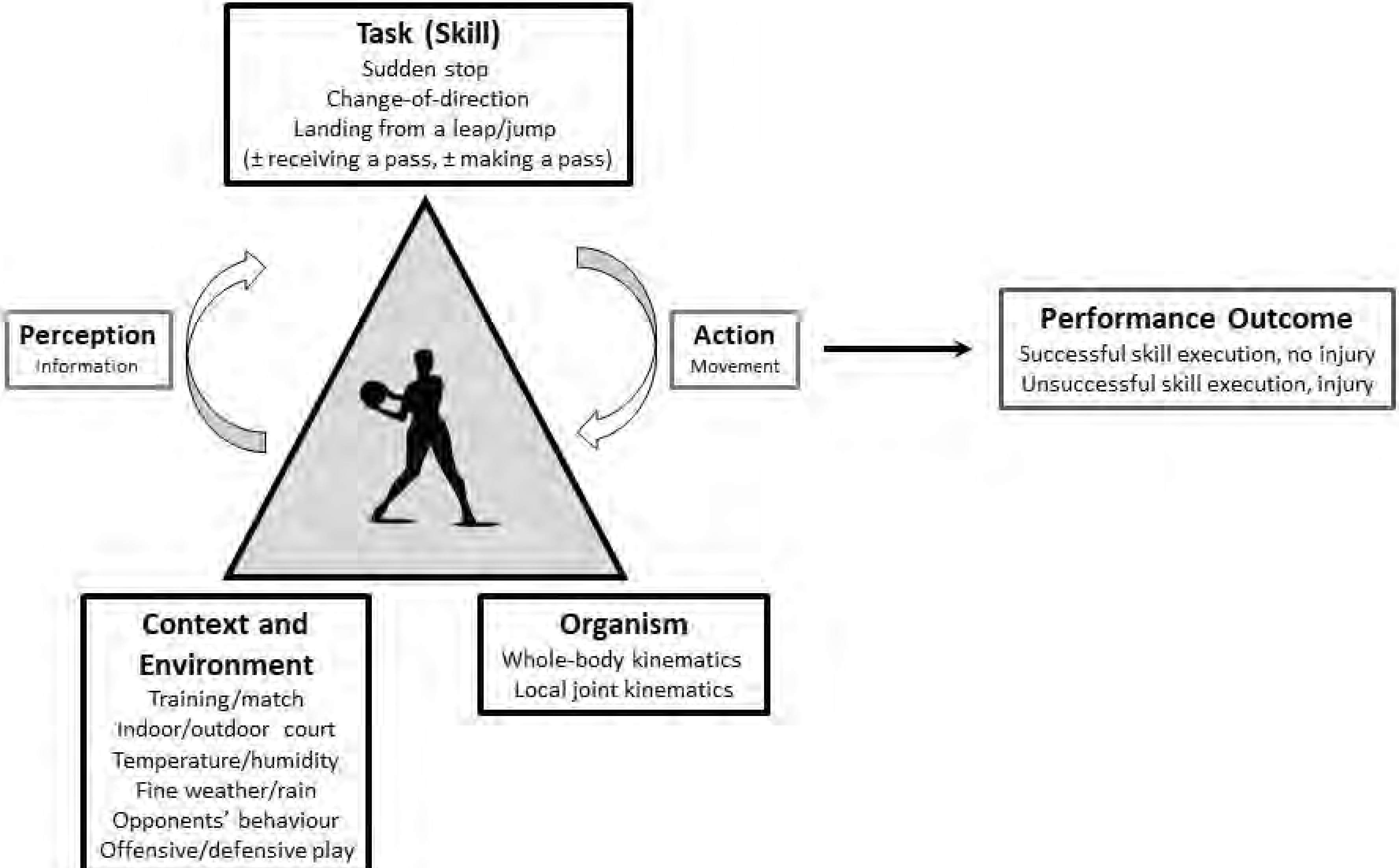
101. Mandelbaum BR, Silvers HJ, Watanabe DS, Knarr JF, Thomas SD, Griffin LY, Kirkendall DT, and Garrett W, Jr. Effectiveness of a neuromuscular and proprioceptive training program in preventing anterior cruciate ligament injuries in female athletes: 2-year follow-up. *The American Journal of Sports Medicine* 33: 1003-1010, 2005.
102. Markolf KL, Burchfield DM, Shapiro MM, Shepard MF, Finerman GA, and Slauterbeck JL. Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research* 13: 930-935, 1995.
103. Marshall SW, Padua DA, and McGrath M. Incidence of ACL injury, in: *Understanding and Preventing Noncontact ACL Injuries*. TE Hewett, SJ Shultz, L Griffin, eds. Illinois: Human Kinetics, 2007.
104. McCurdy K, Walker J, Armstrong R, and Langford G. Relationship Between Selected Measures of Strength and Hip and Knee Excursion During Unilateral and Bilateral Landings in Women. *Journal of Strength and Conditioning Research* 28: 2429-2436, 2014.
105. McCurdy K, Walker J, Saxe J, and Woods J. The Effect of Short-Term Resistance Training on Hip and Knee Kinematics During Vertical Drop Jumps. *Journal of Strength and Conditioning Research* 26: 1257-1264, 2012.
106. McGuine TA, Greene JJ, Best T, and Leverson G. Balance As a Predictor of Ankle Injuries in High School Basketball Players. *Clinical Journal of Sports Medicine* 10: 239-244, 2000.
107. McKenzie CR, Whatman C, Brughelli M, and Borotkanics R. The effect of the NetballSmart Dynamic Warm-up on physical performance in youth netball players. *Physical Therapy in Sport* 37: 91-98, 2019.
108. McManus A, Stevenson MR, and Finch CF. Incidence and risk factors for injury in non-elite netball. *Journal of Science and Medicine in Sport* 9: 119-124, 2006.
109. Meeuwisse WH. Assessing Causation In Sport Injury: A Multifactorial Model. *Clinical Journal of Sport Medicine* 4: 166-170, 1994.
110. Mercado-Palomino E, Richards J, Molina-Molina A, Benitez JM, and Urena Espa A. Can kinematic and kinetic differences between planned and unplanned volleyball block jump-landings be associated with injury risk factors? *Gait Posture* 79: 71-79, 2020.
111. Mizner RL, Chmielewski TL, Toepke JJ, and Tofte KB. Comparison of two-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump. *Clinical Journal of Sport Medicine* 22: 221, 2012.
112. Morrissey MC, Perry MC, and King JB. Is knee laxity change after ACL injury and surgery related to open kinetic chain knee extensor training load? *American Journal of Physical Medicine and Rehabilitation* 88: 369-375, 2009.
113. Mothersole GA, Cronin JB, and Harris NK. Key Prerequisite Factors Influencing Landing Forces in Netball. *Strength and Conditioning Journal* 35: 47-54, 2013.
114. Myer GD, Ford KR, Barber Foss KD, Liu CL, Nick TG, and Hewett TE. The Relationship of Hamstrings and Quadriceps Strength to ACL Injury in Female Athletes. *Clinical Journal of Sports Medicine* 19: 3-8, 2009.
115. Myer GD, Ford KR, Brent JL, and Hewett TE. The Effects of Plyometric vs. Dynamic Stabilization and Balance Training on Power, Balance, and Landing Force in Female Athletes. *Journal of Strength and Conditioning Research* 20: 345-353, 2006.
116. Myer GD, Ford KR, and Hewett TE. Rationale and clinical techniques for anterior cruciate ligament injury prevention among female athletes. *Journal of Athletic Training* 39: 352-364, 2004.
117. Myer GD, Ford KR, and Hewett TE. Tuck jump assessment for reducing anterior cruciate ligament injury risk. *Athletic Therapy Today: The Journal for Sports Health Care Professionals* 13: 39-44, 2008.
118. Myer GD, Ford KR, McLean SG, and Hewett TE. The effects of plyometric versus dynamic stabilization and balance training on lower extremity biomechanics. *The American Journal of Sports Medicine* 34: 445-455, 2006.

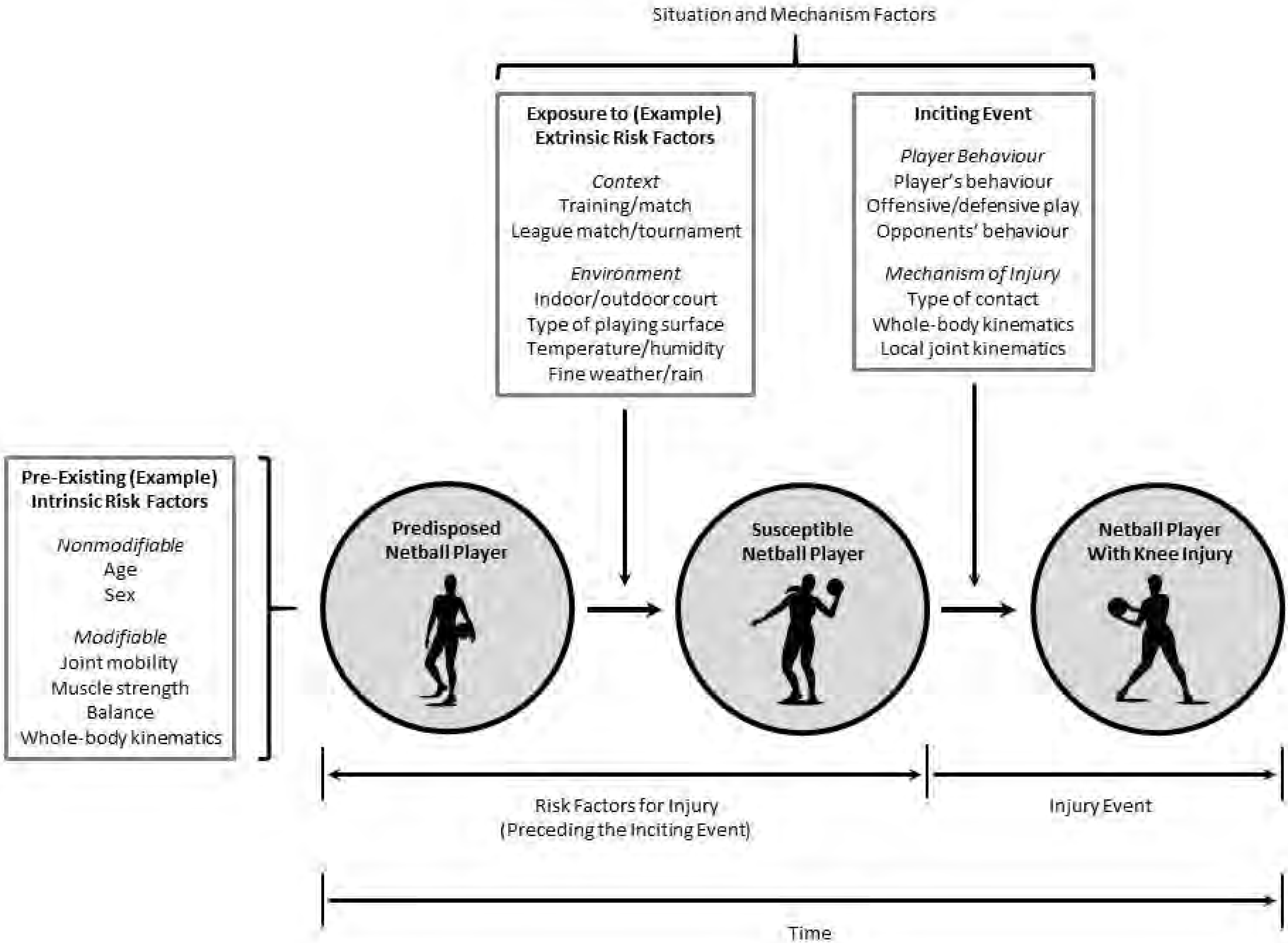
119. Myer GD, Sugimoto D, Thomas S, and Hewett TE. The influence of age on the effectiveness of neuromuscular training to reduce anterior cruciate ligament injury in female athletes: a meta-analysis. *The American Journal of Sports Medicine* 41: 203-215, 2013.
120. Nakagawa TH, Maciel CD, and Serrão FV. Trunk biomechanics and its association with hip and knee kinematics in patients with and without patellofemoral pain. *Manual Therapy* 20: 189-193, 2015.
121. Neely FG. Intrinsic Risk Factors for Exercise-Related Lower Limb Injuries. *Sports Medicine* 26: 253-263, 1998.
122. https://netballamerica.com/communications/fact-sheet/. Accessed June 16/2020.
123. https://knee.netball.com.au/. Accessed June 18/2020.
124. Netball Australia. Annual Report. 2017.
125. https://www.netballsmart.co.nz/. Accessed June 18/2020.
126. Netball New Zealand. Annual report. 2017.
127. Nordin M and Frankel VH. *Basic Biomechanics of the Musculoskeletal System.* Wolters Kluwer/Lippincott Williams and Wilkins Health, 2012.
128. Noyes FR, DeLucas JL, and Torvik PJ. Biomechanics of Anterior Cruciate Ligament Failure: An analysis of Strain-Rate Sensitivity and Mechanisms of Failure in Primates. *The Journal of Bone and Joint Surgery* 56: 236-253, 1974.
129. Noyes FR, Torvik PJ, Hyde WB, and DeLucas JL. Biomechanics of ligament failure: II. An analysis of immobilization, exercise, and reconditioning effects in primates. *The Journal of Bone and Joint Surgery* 56: 1406-1418, 1974.
130. Nyland JA, Shapiro R, Stine RL, Horn TS, and Ireland ML. Relationship of Fatigued Run and Rapid Stop to Ground Reaction Forces, Lower Extremity Kinematics, and Muscle Activation. *Journal of Orthopaedic and Sports Physical Therapy* 20: 132-139, 1994.
131. Okamoto S, Saito R, and Sakamoto M. Intra-rater reliability and criterion-related validity of using an accelerometer to measure the impact force and knee joint sway during single-leg drop landing. *The Journal of Physical Therapy Science* 31: 310-317, 2019.
132. Olsen OE, Myklebust G, Engebretsen L, Holme I, and Bahr R. Exercises to prevent lower limb injuries in youth sports: cluster randomised controlled trial. *British Medical Journal* 330: 449, 2005.
133. Otago L. Kinetic analysis of landings in netball: is a footwork rule change required to decrease ACL injuries? *Journal of Science and Medicine in Sport* 7: 85-95, 2004.
134. Otago L and Peake J. The role of insurance data in setting priorities for netball injury prevention strategies. *Journal of Science and Medicine in Sport* 10: 105-109, 2007.
135. Padua DA, Boling MC, DiStefano LJ, Onate JA, Beutler AI, and Marshall SW. Reliability of the landing error scoring system-real time, a clinical assessment tool of jump-landing biomechanics. *Journal of Sport Rehabilitation* 20: 145-156, 2011.
136. Padua DA, DiStefano LJ, Beutler AI, de la Motte SJ, DiStefano MJ, and Marshall SW. The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury-Prevention Program in Elite-Youth Soccer Athletes. *Journal of Athletic Training* 50: 589-595, 2015.
137. Palmitier RA, An K-N, Scott SG, and Chao EY. Kinetic chain exercise in knee rehabilitation. *Sports Medicine* 11: 402-413, 1991.
138. Parkkari J, Kannus P, Natri A, Lapinleimu I, Palvanen M, Heiskanen M, Vuori I, and Jarvinen M. Active living and injury risk. *International Journal of Sports Medicine* 25: 209-216, 2004.
139. Perry J, Burnfield J, and Burnfield JM. *Gait analysis: normal and pathological function.* SLACK, 2010.
140. Philippe P and Mansi O. Nonlinearity in the epidemiology of complex health and disease processes. *Theoretical Medicine and Bioethics* 19: 591-607, 1998.
141. Pillay T and Frantz JM. Injury Prevalence of Netball players in South Africa: The Need for Injury Prevention. *South African Journal of Physiotherapy* 68: 7-10, 2012.

142. Plisky PJ, Rauh MJ, Kaminski TW, and Underwood FB. Star Excursion Balance Test as a predictor of lower extremity injury in high school basketball players. *Journal of Orthopaedic and Sports Physical Therapy* 36: 911-919, 2006.
143. Pollard CD, Sigward SM, and Powers CM. Limited hip and knee flexion during landing is associated with increased frontal plane knee motion and moments. *Clinical Biomechanics* 25: 142-146, 2010.
144. Portney LG. *Foundations of Clinical Research: Applications to Evidence-Based Practice.* FA Davis, 2020.
145. Qu X and Hu X. Lower-extremity kinematics and postural stability during stair negotiation: effects of two cognitive tasks. *Clinical Biomechanics* 29: 40-46, 2014.
146. Raiola G. Motor learning and teaching method. *Journal of Physical Education and Sport* 17, 2017.
147. Reid DA, Vanweerd RJ, Larmer PJ, and Kingstone R. The inter and intra rater reliability of the Netball Movement Screening Tool. *Journal of Science and Medicine in Sport* 18: 353-357, 2015.
148. Rössler R, Donath L, Verhagen E, Junge A, Schweizer T, and Faude O. Exercise-based injury prevention in child and adolescent sport: a systematic review and meta-analysis. *Sports Medicine* 44: 1733-1748, 2014.
149. Ryman Augustsson S and Ageberg E. Weaker lower extremity muscle strength predicts traumatic knee injury in youth female but not male athletes. *British Medical Journal Open Sport and Exercise Medicine* 3: e000222, 2017.
150. Ryman Augustsson S, Augustsson J, Thomee R, Karlsson J, Eriksson BI, and Svantesson U. Performance Enhancement Following a Strength and Injury Prevention Program: A 26-Week Individualised and Supervised Intervention in Adolescent Female Volleyball Players. *International Journal of Sports Science and Coaching* 6: 399-417, 2011.
151. Schnurrer-Luke Vrbanić T, Ravlic-Gulan J, Gulan G, and Matovinovic D. Balance Index Score as a Predictive Factor for Lower Sports Results or ACL Knee Injuries in Croatian Female Athletes - Preliminary Study. *Collegium Antropologicum* 31: 253-258, 2007.
152. Schurr SA, Marshall AN, Resch JE, and Saliba SA. Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *International Journal of Sports Physical Therapy* 12: 163-172, 2017.
153. Self BP and Paine D. Ankle biomechanics during four landing techniques. *Medicine and Science in Sports and Exercise* 33: 1338-1344, 2001.
154. Sell TC, Ferris CM, and Abt JP. The Effect of Direction and Reaction on the Neuromuscular and Biomechanical Characteristics of the Knee during Tasks that Simulate the Noncontact Anterior Cruciate Ligament Injury Mechanism. *The American Journal of Sports Medicine* 34: 43-54, 2006.
155. Sell TC, Ferris CM, Abt JP, Tsai YS, Myers JB, Fu FH, and Lephart SM. Predictors of proximal tibia anterior shear force during a vertical stop-jump. *Journal of Orthopaedic Research* 25: 1589-1597, 2007.
156. Sheehan FT, Sipprell WH, 3rd, and Boden BP. Dynamic sagittal plane trunk control during anterior cruciate ligament injury. *The American Journal of Sports Medicine* 40: 1068-1074, 2012.
157. Shimokochi Y, Ambegaonkar JP, Meyer EG, Lee SY, and Shultz SJ. Changing sagittal plane body position during single-leg landings influences the risk of non-contact anterior cruciate ligament injury. *Knee Surgery, Sports Traumatology, Arthroscopy* 21: 888-897, 2013.
158. Shin CS, Chaudhari AM, and Andriacchi TP. Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine and Science in Sports and Exercise* 43: 1484-1491, 2011.

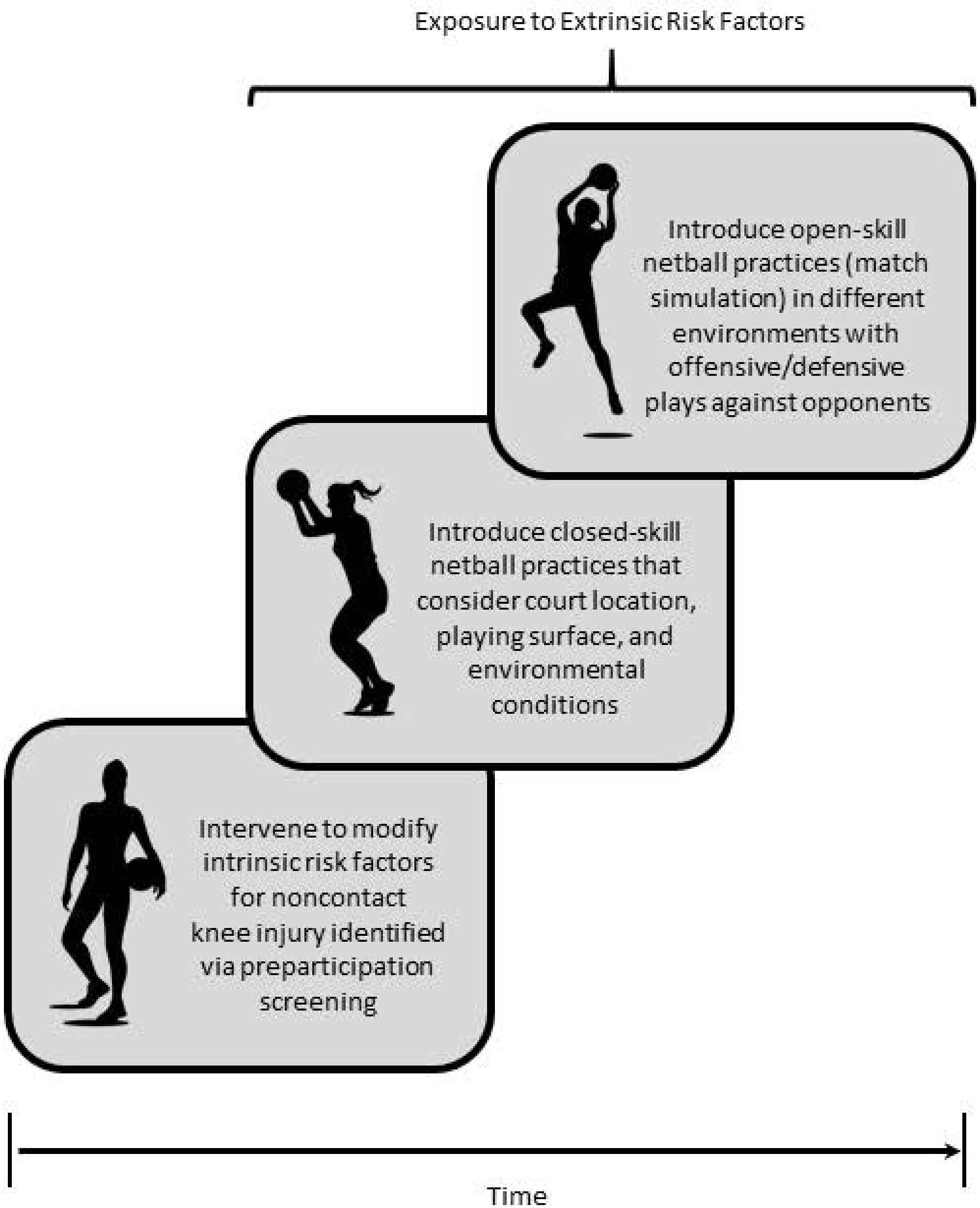
159. Sinclair J, Taylor PJ, and Foxcroft H. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during single-and double-limb post-catch deceleration strategies in university netballers. *Sport Sciences for Health* 15: 215-222, 2019.
160. Sinclair JK, Vincent H, and Richards JD. Effects of prophylactic knee bracing on knee joint kinetics and kinematics during netball specific movements. *Physical Therapy in Sport* 23: 93-98, 2017.
161. Smith MM, Mendis MD, Parker A, Grantham B, Stewart S, and Hides J. Injury surveillance of an Australian community netball club. *Physical Therapy in Sport* 44: 41-46, 2020.
162. Sorenson B, Kernozek TW, Willson JD, Ragan R, and Hove J. Two-and three-dimensional relationships between knee and hip kinematic motion analysis: single-leg drop-jump landings. *Journal of Sport Rehabilitation* 24: 363-372, 2015.
163. Steele JR. Biomechanical Factors Affecting Performance in Netball. Implications for Improving Performance and Injury Reduction. *Sports Medicine* 10: 88-102, 1990.
164. Steele JR and Chad KE. An analysis of the movement patterns of netball players during match play: implications for designing training programs. 1991.
165. Steele JR and LaFortune MA. A Kinetic Analysis of Footfall Patterns at Landing in Netball: A Follow-up Study, in: *International Society of Biomechanics in Sports Conference* 1989.
166. Steele JR and Milburn PD. Ground reaction forces on landing in netball. *Journal of Human Movement Studies* 13: 399-410, 1987.
167. Steele JR and Milburn PD. Effect of Different Synthetic Sport Surfaces on Ground Reaction Forces at Landing in Netball. *International Journal of Sports Biomechanics* 4: 130-145, 1988.
168. Stein T, Mehling AP, Welsch F, von Eisenhart-Rothe R, and Jager A. Long-term outcome after arthroscopic meniscal repair versus arthroscopic partial meniscectomy for traumatic meniscal tears. *The American Journal of Sports Medicine* 38: 1542-1548, 2010.
169. Stephenson ML, Hinshaw TJ, Wadley HA, Zhu Q, Wilson MA, Byra M, and Dai B. Effects of timing of signal indicating jump directions on knee biomechanics in jump-landing-jump tasks. *Sports Biomechanics* 17: 67-82, 2018.
170. Stuelcken M, Greene A, Smith R, and Vanwanseele B. Knee loading patterns in a simulated netball landing task. *European Journal of Sport Science* 13: 475-482, 2013.
171. Stuelcken MC, Mellifont DB, Gorman AD, and Sayers MG. Mechanisms of anterior cruciate ligament injuries in elite women's netball: a systematic video analysis. *Journal of Sports Science* 34: 1516-1522, 2016.
172. Sugimoto D, Myer GD, Foss KDB, and Hewett TE. Specific exercise effects of preventive neuromuscular training intervention on anterior cruciate ligament injury risk reduction in young females: meta-analysis and subgroup analysis. *British Journal of Sports Medicine* 49: 282-289, 2015.
173. Suzuki H, Omori G, Uematsu D, Nishino K, and Endo N. The Influence of Hip Strength on Knee Kinematics During a Single-legged Medial Drop Landing Among Competitive Colleagiate Basketball Players. *The International Journal of Sports Physiotherapy* 10: 592-601, 2015.
174. Thomas C, Comfort P, Jones PA, and Dos'Santos T. Strength and Conditioning for Netball. *Strength and Conditioning Journal* 39: 10-21, 2017.
175. Tipton CM, James SL, Mergner W, and Tcheng T-K. Influence of exercise on strength of medial collateral knee ligaments of dogs. *American Journal of Physiology-Legacy Content* 218: 894-902, 1970.
176. Trentacosta NE, Vitale MA, and Ahmad CS. The effects of timing of pediatric knee ligament surgery on short-term academic performance in school-aged athletes. *The American Journal of Sports Medicine* 37: 1684-1691, 2009.
177. van Mechelen W, Hlobil H, and Kemper HCG. Incidence, Severity, Aetiology and Prevention of Sports Injuries. A Review of Concepts. *Sports Medicine* 14: 82-99, 1992.

178. Vanwanseele B, Stuelcken M, Greene A, and Smith R. The effect of external ankle support on knee and ankle joint movement and loading in netball players. *Journal of Science and Medicine in Sport* 17: 511-515, 2014.
179. Verhagen E, van Dyk N, Clark N, and Shrier I. Do not throw the baby out with the bathwater; screening can identify meaningful risk factors for sports injuries. *British Journal of Sports Medicine* 52: 1223-1224, 2018.
180. Vescovi JD, Canavan PK, and Hasson S. Effects of a plyometric program on vertical landing force and jumping performance in college women. *Physical Therapy in Sport* 9: 185-192, 2008.
181. Wang CH, Chang CC, Liang YM, Shih CM, Chiu WS, Tseng P, Hung DL, Tzeng OJ, Muggleton NG, and Juan CH. Open vs. closed skill sports and the modulation of inhibitory control. *PLoS One* 8: e55773, 2013.
182. Webster KE and Hewett TE. Meta-analysis of meta-analyses of anterior cruciate ligament injury reduction training programs. *Journal of Orthopaedic Research®* 36: 2696-2708, 2018.
183. Whiting WC and Zernicke RF. *Biomechanics of Musculoskeletal Injury.* Human Kinetics, 2008.
184. Williams R and O'Donoghue P. Lower limb injury risk in netball: a time-motion analysis investigation. *Journal of Human Movement Studies* 49: 315-331, 2005.
185. Williams SA, Ng L, Stephens N, Klem N, and Wild C. Effect of prophylactic ankle taping on ankle and knee biomechanics during basketball-specific tasks in females. *Physical Therapy in Sport* 32: 200-206, 2018.
186. Willson JD, Ireland ML, and Davis I. Core strength and lower extremity alignment during single leg squats. *Medicine and Science in Sports & Exercise* 38: 945-952, 2006.
187. Woo SL, Abramowitch SD, Kilger R, and Liang R. Biomechanics of knee ligaments: injury, healing, and repair. *Journal of Biomechanics* 39: 1-20, 2006.
188. Yu B, Lin CF, and Garrett WE. Lower extremity biomechanics during the landing of a stop-jump task. *Clinical Biomechanics* 21: 297-305, 2006.
189. Zahradnik D, Uchytil J, Farana R, and Jandacka D. Ground Reaction Force and Valgus Knee Loading during Landing after a Block in Female Volleyball Players. *Journal of Human Kinetics* 40: 67-75, 2014.
190. Zazulak BT, Hewett TE, Reeves NP, Goldberg B, and Cholewicki J. Deficits in Neuromuscular Control Of The Trunk Predict Knee Injury Risk: A Prospective Biomechanical-Epidemiologic Study. *The American Journal of Sports Medicine* 35: 1123-1130, 2007.
191. Zhang S, Bates BT, and Dufek JS. Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise* 32: 812-819, 2000.


Task (Skill)
Sudden stop
Change-of-direction
Landing from a leap/jump
(± receiving a pass, ± making a pass)
Perception
Information
Action
Movement
Performance Outcome
Successful skill execution, no injury
Unsuccessful skill execution, injury
Context and Environment
Training/match
Indoor/outdoor court
Temperature/humidity
Fine weather/rain
Opponents' behaviour
Offensive/defensive play
Organism
Whole-body kinematics
Local joint kinematics



Situation and Mechanism Factors
Exposure to (Example) Extrinsic Risk Factors
Context
Training/match
League match/tournament
Environment
Indoor/outdoor court
Type of playing surface
Temperature/humidity
Fine weather/rain
Inciting Event
Player Behaviour
Player's behaviour
Offensive/defensive play
Opponents' behaviour
Mechanism of Injury
Type of contact
Whole-body kinematics
Local joint kinematics
Pre-Existing (Example) Intrinsic Risk Factors
Nonmodifiable
Age
Sex
Modifiable
Joint mobility
Muscle strength
Balance
Whole-body kinematics
Predisposed Netball Player
Susceptible Netball Player
Netball Player With Knee Injury
Risk Factors for Injury (Preceding the Inciting Event)
Injury Event
Time



Exposure to Extrinsic Risk Factors
Introduce open-skill netball practices (match simulation) in different environments with offensive/defensive plays against opponents
Introduce closed-skill netball practices that consider court location, playing surface, and environmental conditions
Intervene to modify intrinsic risk factors for noncontact knee injury identified via preparticipation screening
Time

Table 1. Example factors in analysing and understanding a knee injury event*

Situation Factors	Mechanism Factors
When the injury occurred	*Type of contact*
Training, match (e.g. which quarter of the match)	Direct contact, indirect contact, noncontact
Where the injury occurred	*Pattern of whole-body kinematics*
Indoors vs outdoors, type of playing surface (e.g. timber, asphalt)	Player's trunk position and motion at the instant-of-injury (e.g. lateral flexion towards injured leg)
What the environmental conditions were	*Pattern of local joint kinematics*
Ambient temperature, ambient humidity, rain vs no rain	Player's knee position and motion at the instant-of-injury (e.g. abduction, anterior tibial displacement, internal-rotation)
What the opponents were doing	
Offensive play, defensive play	
What the player's team was doing	
Offensive play, defensive play	
What the player was doing	
Running sudden stop, running change-of-direction, landing from a jump/leap, receiving a pass, making a pass	

*Modified from: 7, 86, 171

Table 2. Contact, indirect contact, and noncontact nature of knee injury*

Classification and Definition	Example
Contact injury	
Following contact with the player's knee from an opponent or external object	When a direct blow to the player's knee occurs from an opponent who slips/trips/falls onto the player
Indirect contact injury	
Following contact with another part of the player's body (e.g. trunk) from an opponent or external object	When competing for the ball side-by-side with an opponent
Noncontact injury	
Following an athletic maneuver without any contact from an opponent or external object	When a player decelerates suddenly while cutting to change direction when running or when landing from a leap

*Modified from: 87, 103, 171

Table 3. Components and tests in the Netball Movement Screening Tool*

Movement Competency Screen Component	Jump Screen Component	Star Excursion Balance Test Component	Active Straight Leg Raise Component
BW double-leg squat	Double-leg vertical jump	Anterolateral reach	Supine ASLR
BW single-leg squat	Single-leg vertical jump	Posteromedial reach	
Lunge + twist	Broad jump	Posterolateral reach	
Push-up			
Bend + pull			

*from reference 147: see this citation for scoring information
BW = bodyweight; ASLR = active straight-leg raise

Table 4. Example netball-specific noncontact knee injury prevention preparticipation screening tests*

Physical Characteristic	Test	Suitable Variable	Related Study
Ankle joint DF mobility	Straight-knee passive DF ROM with a goniometer	°	55
	Weightbearing lunge test	cm	80
Lower-limb muscle strength	1RM modified barbell single-leg squat	%BW, LSI, A-A	114
	1RM single-leg leg-press	%BW, LSI, A-A	26
Hip muscle strength	Side-lying straight-leg hip abduction isometric strength with an HHD	%BW, LSI, A-A	182
	Prone bent-knee hip ER isometric strength with an HHD	%BW, LSI, A-A	182
Knee muscle strength	1RM single-leg knee extension	%BW, LSI, A-A	26
	1RM single-leg knee flexion	%BW, LSI, A-A	26
Ankle muscle strength	1RM standing single-leg straight-leg calf-raise	%BW, LSI, A-A	19
	1RM seated single-leg bent-leg calf-raise	%BW, LSI, A-A	85
Trunk muscle strength	Side-bridge isometric strength with an HHD	%BW	130
	Side-bridge isometric hold	s	195
Balance	Eyes-closed single-leg balance	s, LSI, A-A	24,25
	Star Excursion Balance Test Anterior/posteromedial/posterolateral	%LL, LSI, A-A	148
Lower-limb movement patterns	2D high-definition video single-leg drop-vertical-jump	Peak ipsilateral trunk lean angle, ° Peak knee abduction angle, °	38
	2D high-definition video single-leg squat	Peak ipsilateral trunk lean angle, ° Peak knee abduction angle, °	67
	LESS-RT	Composite score**	141
	QASLS	Composite score**	68
Functional performance tests	Single-hop-for-distance	%LL, %H, LSI, A-A	24,25
	Triple-hop-for-distance	%LL, %H, LSI, A-A	24,25

	Vertical-hop	%LL, %H, LSI, A-A	25

*all single-leg tests are performed for both right and left sides.
DF = dorsiflexion; ROM = range-of-motion; ° = degrees; cm = centimeters; 1RM = one repetition maximum;
%BW = percentage of bodyweight = (weight lifted (kg) ÷ bodyweight (kg)) × 100;
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);
HHD = handheld dynamometer; ER = external rotation; s = seconds; 2D = two dimensional; LESS-RT = Landing Error Scoring System-Real Time; QASLS = Qualitative Analysis of Single-Leg Squat;
%LL = percentage of leg-length = (distance hopped (cm) ÷ leg-length (cm)) × 100;
%H = percentage of standing height = (distance hopped (cm) ÷ standing height (cm)) × 100.
** = see Related Study citation for scoring system.

Table 5. Suggested fundamental double-leg and single-leg alignment/landing principles for plyometric training*

Double-Leg, Sagittal Plane - Right/Left Side View	**Double-Leg, Frontal Plane - Front/Back View**	**Single-Leg, Sagittal Plane - Stance-Leg Side View**	**Single-Leg, Frontal Plane - Front/Back View**
Face and eyes directed forwards	Face and eyes directed forwards	Face and eyes directed forwards	Face and eyes directed forwards
Trunk inclined forwards via hip hinge	Head, sternum, and navel in a vertical straight line	Trunk inclined forwards via hip hinge	Head, sternum, and navel in a vertical straight line
Back straight with hips over heels	Shoulders level in a horizontal straight line	Back straight with hip over heel	Shoulders level in a horizontal straight line
Knees flexed, ankles dorsiflexed	Iliac crests level in a horizontal straight line	Knee flexed, ankle dorsiflexed	Iliac crests level in a horizontal straight line
Heels aligned in a horizontal straight line	Hips, knees, ankles in a vertical straight line	Swing-leg held comfortably flexed, toes just off ground	Hips, knees, ankles in a diagonal straight line
Heels and toes level on ground	Feet pointing in self-selected direction	Heel and toes level on ground	Foot pointing in self-selected direction
			Navel and first toe in a vertical straight line

*Modified from: 113

Table 6. Example preseason single-week microcycle for community-level netball players

Weekday	**Morning**	**Afternoon/Evening**
Monday	Work	Individualized multi-modal exercise training session
Tuesday	Work	Team-level netball skills/tactics training session
Wednesday	Work	Aerobic energy system training
Thursday	Work	Anaerobic energy system training
Friday	Work	Rest
Saturday	Match	Rest
Sunday	Rest	Rest

Table 7. Example preseason individualized multi-modal exercise training session*

Component	Exercise**	Program Variables
Warm-up	Hip and ankle mobility Aerobic warm-up DL BW squats Forward BW lunges SL BW calf-raises	2 x 30 seconds 3-5 minutes 1 set x 10 repetitions 1 set x 10 repetitions 1 set x 10 repetitions
Plyometric training	SL vertical hop and stick SL lateral hop and stick SL forward leap and stick SL lateral leap and stick SL diagonal leap and stick DL squat jump and stick with 180° rotation to right DL squat jump and stick with 180° rotation to left Broad jumps	1 set x 6-8 repetitions
Balance training	SL balance and catch netball (bouncing ball to self on/off wall) SL BOSU balance (hard-side up) SL balance on floor with eyes closed	1 set x 2 repetitions, 30 seconds/repetition
Closed kinetic chain strength training	Dumbbell lunges SL dumbbell/kettlebell deadlift SL Machine/DB Calf Raise	2-3 sets x 6-8 repetitions
Open kinetic chain strength training	SL leg extension SL leg curl	2-3 sets x 6-8 repetitions
Core training	Isometric side-plank Bird-dog	2-3 sets x 6-8 repetitions
Cool-down	Aerobic activity (e.g. walking, step-ups) Stretches (quadriceps, hamstrings, gluteals, hip adductors, hip flexors, gastrocnemius, soleus)	5 minutes 1 x 1-2 repetitions, 30-60 seconds/repetition

*Load for strength exercises will be individualized relative to desired number of repetitions

**single-leg exercises are repeated on right and left sides

DL= double-leg; BW=bodyweight; SL = single-leg;

Table 8. Example preseason generic multi-modal 15-minute warm-up for all players prior to a team-level netball skills/tactics training session

Component	Exercise*	Program Variables
CV/Pulse Raiser	Walking A's Straight line running Forwards and backwards running Run circling partner Butt flicks and skipping Leg Taps with partner	To halfway point of court x 2 2 x 30 seconds
Mobility	Ankle – standing bent-knee DF Hip – open and close the gate, walking dynamic stretches of hamstrings, gluteals, quadriceps	Repeat repetitions 2 x 30 seconds To halfway point of court x 2
Strengthening	Power Tower with partner BW Squats Arabesque Reverse lunge and drive	2 x 30 seconds 3 sets x 5 repetitions each exercise
Balance	SL Balance (add partner push) SL Balance with passes left/right/up/down	1 minute each leg
Plyometrics/Landing	Vertical jumps Jump, turn and land Vertical hops Horizontal hops Horizontal leaps Lateral leaps	2 sets x 5 repetitions – focus on landing technique 2 sets x 5 repetitions – focus on landing technique 2 sets x 5 repetitions – focus on landing technique
Netball Specific	Shuffle forwards and backwards (fast feet over the backline) Lateral shuffles (while moving forwards and backwards) Run and jump with shoulder contact with partner Run and stop Run, plant and cut	3 x 30 seconds To halfway point of court x 2

*single-leg exercises are repeated on right and left sides

Table 9. Example preseason single-session aerobic energy system training program

Training Method	Exercise	Program Variables
Warm-Up	5-minute walk Hip and ankle mobility	5/10 RPE 50-60% MHR 2 x 30 seconds
Continuous	Running Cross-Trainer/Elliptical Cycling	20 minutes steady state 65-75% MHR
Long Interval Training	Running Cross-Trainer/Elliptical Cycling	4 minutes work/1 minute recovery Repeat x 5
Cool-Down	5-minute walk Whole Body Stretches	 Hold all for at least 30 seconds

RPE = Rate of Perceived Exertion

MHR = Maximum Heart Rate

Table 10. Example preseason single-session anaerobic energy systems training program

Training Method	Exercise	Program Variables
Warm-Up	5-minute walk Hip and ankle mobility	50-60% MHR 5/10 RPE 2 x 30 seconds
Sprints	Straight line sprints Run and stop	5-10 meter sprints x 5 repetitions
HIIT	Run/walk intervals	1:5 work: rest ratio
COD drills	Cone COD drills Ladder footwork drills	10 x 20 seconds
Cool-Down	5-minute walk Whole Body Stretches	 Hold all for at least 30 seconds

MHR = Maximum Heart Rate

RPE = Rate of Perceived Exertion

HIIT = High Intensity Interval Training

COD = Change of Direction