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

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**Noncontact Knee Soft Tissue Injury Prevention
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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 BF_s, 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 $\leq 64\%$ 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

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Exposure to Extrinsic Risk Factors

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

Situation Factors	Mechanism Factors
<i>When the injury occurred</i>	<i>Type of contact</i>
Training, match (e.g. which quarter of the match)	Direct contact, indirect contact, noncontact
<i>Where the injury occurred</i>	<i>Pattern of whole-body kinematics</i>
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)
<i>What the environmental conditions were</i>	<i>Pattern of local joint kinematics</i>
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)
<i>What the opponents were doing</i>	
Offensive play, defensive play	
<i>What the player's team was doing</i>	
Offensive play, defensive play	
<i>What the player was doing</i>	
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
<i>Contact injury</i>	
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
<i>Indirect contact injury</i>	
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
<i>Noncontact injury</i>	
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	5/10 RPE 50-60% MHR
	Hip and ankle mobility	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