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Original Research Article

Protective Compensatory Mechanisms and Biomechanical Load Distribution in ACL–Inhibited Netball Players: An Inverse Dynamics Analysis

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Abstract

Objectives: This study aims to investigate protective compensatory mechanisms and biomechanical load distribution on the lower limb joints in ACL-inhibited netball players. ***Design:*** Cross-sectional study and stratified participant sampling. *Setting:* Experimental lab-based. *Participants:* Five ACL-inhibited female netball players and a control group of 7 non-injured players of university recreational level took part in the study. ***Outcome measures:*** The participants performed 3 netball skills: cutting, and stop jump, and vertical jump. A Bertec force platform (960 Hz), a Qualisys automated motion capture system (120 Hz) and inverse dynamics analysis were used to obtain sagittal plane kinematics, ground reaction forces (GRFs), and joint kinetics at the hip, knee and ankle. Biomechanical variables measured included peak flexion, dorsiflexion, angular velocity, GRF components, loading rate, compressive and shear forces, and joint moments at the hip, knee and ankle. ***Results:*** The highest shear joint forces occurred in the cutting movement. However, the ACL-inhibited group showed the lowest shear and moments at the knee joint, whereas the non-injured group experienced the largest shear forces at the knee. ***Conclusions:*** The findings suggest the presence of protective compensatory mechanisms in ACL-inhibited players which consist of lower relative shear forces and moments at the injured knee joint.

Keywords: anterior cruciate ligament, biomechanics, functional rehabilitation, kinetics, knee-joint, motion-analysis.

INTRODUCTION

Netball presents a high incidence of anterior cruciate ligament (ACL) injuries compared to other sports [1]. The injury typically occurs during cutting actions, stop jumps, and sudden decelerations [2], whereby the centre playing position sustains the highest frequency of injury [3]. Previous studies have explored the kinetics of landing from a vertical drop [4] and the kinematics of the various landing techniques that occur in a netball match [2, 5]. Recent research has analysed the loading patterns in the frontal plane sustained by netball players [6] as this is a significant factor in the development of acute and chronic knee injuries if females [7].

Female athletes show a higher frequency of knee injuries to the ACL [1, 8, 9]. This is attributed to a combination of factors; excessive knee valgus observed in females at landing as a consequence of non-neutral alignment of the hips, causing an over balance of the varus/valgus opening mechanism [9]. Females also show a tendency to land with the knee and ankle in a more extended position compared to their male counterparts, thus eliciting a greater risk of non-contact ACL injuries [10, 11]. The increased risk for ACL injury in female athletes is multifactorial, consisting of extrinsic factors (body movement, muscular strength, shoe-surface interface, and skill level) and intrinsic factors (joint laxity, limb alignment, ligament size, and hormonal influences) [12, 13]. Research is evident in the kinetic and kinematic analysis related to intermittent team sport movements such as the ‘dodging’ technique or ‘cutting’ manoeuvre [8, 14-17]. This places stress on the knee and ankle joints across the frontal plane [10, 18-20] with a heightened torso tilt in the frontal plane angle of the torso from vertical, alongside a greater knee abduction shown in female athletes at initial contact [14]. Injury is also more likely to occur in episodes of increased rate of direction change during the game as these cause a drastic reduction in knee peak torque compared to play with fewer directional changes [21, 22]. Ardern *et al.*, [23] reported that following ACL-reconstruction surgery only 18.5% of players returned to competitive netball. If rehabilitation criteria have not been fully met, deficits in lower extremity proprioception and strength, and ground reaction force (GRF) attenuation can occur [24-26].

Research into biomechanical loading abnormalities in ACL-inhibited players is lacking, therefore this study aimed to assess kinematics, GRFs and biomechanical loading distribution on the lower limb joints to identify whether protective compensatory mechanisms are present in selected netball game skills (cutting, stop jump landing and vertical jump landing) in ACL-inhibited netballers upon their return to recreational netball. It was hypothesised that ACL-inhibited players show greater biomechanical loads in the hip and ankle joints to take the strain off the knee. The findings can provide insight into abnormal biomechanical loading adaptations to landing that may predispose netball players to re-injury.

METHODS

This experimental lab-based cross-sectional study used a stratified design to include both ACL-inhibited and non-injured participants. The independent variables included: injury status x 2 (ACL-inhibited netball players, experimental group; and non-injured players, control group), joint x 3 (hip, knee and ankle), GRF force component x 3 (peak vertical Fz, anterior/posterior Fy and medio/lateral Fx), and netball skill x 3 (cutting, stop jump, and vertical jump). The dependent variables obtained from the landing phase of the movements were kinematic variables derived using a Qualisys motion analysis system including peak hip flexion, knee flexion and ankle dorsiflexion, and peak angular velocity (maximum rate of flexion) of the same from the injured leg (experimental group) or dominant leg (control group) [27]. Peak GRF Fz, Fy and Fx, and loading rates were normalised to body weight. Compressive and shear forces and moments at the hip, knee and ankle were calculated using inverse dynamics and normalised to body weight [27]. Covariates included approach velocity and jump height from the run up and preparatory phases of the movements.

Twelve female university netball players from the North of England participated in this study. The experimental group consisted of 5 ACL-inhibited players and a control group was composed of 7 non-injured players. Demographic data and comparisons across the two groups of players using independent *t*-tests are reported in Table-1. The ACL-inhibited participants were asked to complete an Injury History Questionnaire to identify their injury history, ACL reconstruction surgery and rehabilitation program (Table-2). The Injury History Questionnaire helped monitor confounding variables (e.g., severity of the ACL injury, type of rehabilitation received) [2, 3, 28, 29]. Injury history included full ACL reconstruction in one or both knees, ACL strain alongside cartilage damage, and reoccurring knee sprains from weakened ACL. The participant inclusion criteria required ACL-inhibited participants to be clear from the doctor's from lower limb injury for 12 months, to ensure efficient recovery to return to recreational sport and perform near their full ability [23]. Ethical approval for the study was granted by the Institution's Ethics Committee.

Table-1: Demographics of the participants

	ACL-inhibited	Non-injured	Independent *t*-test
Age (yrs)	20.6 ± 0.9	19.0 ± 1.0	t = 2.85, df = 10, p = 0.017
Height (cm)	167.4 ± 8.2	170.6 ± 4.9	t = -0.85, df = 10, p = 0.414
Mass (kg)	74.5 ± 8.1	71.9 ± 13.8	t = 0.37, df = 10, p = 0.721

Table-2: Description of injury history, reconstruction surgery and rehabilitation program in the ACL-inhibited group

Participant	Injury History	ACL Reconstruction Surgery	Rehabilitation Program
NOTES	-	Players 1 and 2 underwent ACL reconstruction surgery consisting of hamstring autograft reconstruction.	All players received physiotherapy. The extent of the physiotherapy intervention varied amongst participant.
1	Participant 1 incurred three previous injuries to the ACL. The first incidence was a partial tear as a result of a contact injury, the second another partial tear from a non-contact injury, and the third a full rupture from a non-contact injury where she received reconstruction surgery. There was one year recovery between each incidence.	The player received reconstruction surgery following the full rupture from a non-contact injury.	Participant 1 received NHS lead physiotherapy for the partial tears for 2 months, stability training, and rehabilitation to prevent hamstrings and quadriceps muscle wastage. After the complete rupture, she received physiotherapy from a 'Bupa' sports therapist for 4 months, and completed gentle plyometrics and isokinetic dynamometry measurements.
2	Participant 2 sustained a complete rupture to the ACL alongside scar tissue damage to the MCL.	The ACL required reconstruction surgery.	Participant 2 received ongoing physiotherapy for 3 years after the injury.

3	Participant 3 received a suspected tear to the ACL alongside cartilage damage. An arthroscopy was conducted to identify the extent of the damage, which identified a severe strain to the ACL. The knee was then 'cleaned' and flushed of any debris during the surgery.	No reconstruction surgery	Participant 3 received physiotherapy for 6-8 weeks prior to and post arthroscopy to prevent muscle wastage before and after arthroscopy surgery.
4	Participant 4 sustained an ACL strain alongside cartilage damage. This injury re-occurred in the exact same way a year later.	No reconstruction surgery	Participant 4 received physiotherapy treatment for 2 weeks after her injury.
5	Participant 5 reported a permanently weakened ACL with 'worn away' cartilage as a result of overuse injuries. This causes the knee to 'give way' often and leg weakness to re-occur regularly.	No reconstruction surgery	Participant 5 received ongoing physiotherapy for 4 years after the injury.

Prior to testing, the participants performed a standardised netball warm up [28]. During data collection, the participants were instructed to use an approach that felt natural to how they would perform during a game situation and to land on a force platform (Bertec, QTM v 2.0.365, USA) operating at 960 Hz. A Qualisys Pro-reflex infra-red automated motion analysis system (Qualisys, Sweden) consisting of six infra-red cameras operating at a sampling frequency of 120 Hz recorded the motion of the participants. [5] Fifteen 2-cm reflective markers were place on selected anatomical landmarks, including the bilateral anterior superior iliac spine, medial and lateral epicondyle of the femur, medial and lateral malleolus, calcaneus, head of the second metatarsal bone, sacrum, and 7th vertebrae. A single experimenter placed the reflective markers on all the participants to increase the reliability of marker positioning [5].

For the cutting movement, the ACL-inhibited participants were asked to identify their injured leg and the non-injured participants their dominant leg and to use that leg to perform the cutting manoeuvre and to land on the force plate in the stop and vertical jumps. Leg dominance was determined by asking the non-injured participants what was their preferred leg for cutting, and was established during the familiarization trials. The ball pass (standard Gilbert netball) for the cutting movement was received directly after the 'cut' was performed and the ball feeder was positioned approximately 5 m away from the landing area at 5° angle to the right relative to the approach direction (Fig-1) [5]. In the stop jump, the players received a chest pass using the netball directly as they landed on to the force platform with their injured or dominant leg. In the vertical jump, the participants were required to stand directly behind the force platform. Then, they waited for the ball pass, which was received directly above their head. A vertical jump was performed to reach the ball, followed by landing onto the platform with their injured or dominant leg, thus re-enacting an 'interception'.

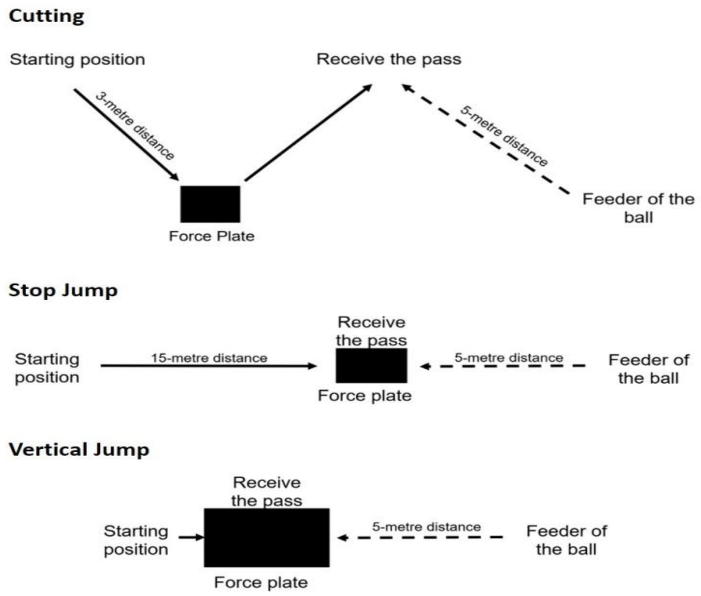

Fig-1: Layout of the execution of the netball skills

Statistical analyses were carried out using SPSS software (IBM SPSS Statistics 24). Descriptive statistics consisted of means and SDs. Exploratory data analysis (EDA) was performed on the two covariates (approach velocity and jump height) that may influence lower joint kinematics, GRFs and joint kinetics using independent t-tests and scatterplots. Two-way and three-way Ancova models contained two independent variables (injury status and lower limb joint) or three independent variables (injury status, lower limb joint, and force component), while controlling for the effect of approach velocity and jump height as covariates [30]. Statistical assumption for Ancova [30] were checked, including: 1. absence of outliers using Cook's distance and normality of data distribution (of both raw data and residuals); 2. homogeneity of variance and heteroscadisticity of residuals; 3. Covariates not strongly correlated to one another (the assumption was met, *r* range = -0.01 – 0.415, *p* range = 0.18 – 0.98); 4. Linear relationship between covariates and dependent variables; and 5. Homogeneity of regression slopes (the assumption was met, *p* range = 0.20 – 0.58). Deviations from normality of the raw data were minor (Shapiro Wilk, *p* range = 0.03 – 0.85), therefore the raw data were used for the Ancova tests, since Ancova is known to be robust to minor infringements of the normality assumption [30]. The assumption of linearity of the relationship between covariates and dependent variables was generally met, however the relationship was slightly curvilinear in some data sets. Probability level was set at $p < 0.05$ for all tests, and post-hoc *p* values were computed using a Bonferroni-Holm alpha error adjustment (0.05/(levels – rank +1)) [30]. Partial eta squared (η_p^2) was interpreted based upon the guidelines of Cohen [30] in which η_p^2 of 0.02 is small, 0.13 is medium, and 0.26 is large.

RESULTS

The three netball skills were dominated by hip kinematic action, whereby peak flexion was highest at the hip in all netball skills, followed in magnitude by the knee and then the ankle (Fig-2). ACL-inhibited players exhibited greater joint flexion than non-injured players in the stop jump, but less flexion in the vertical jump.

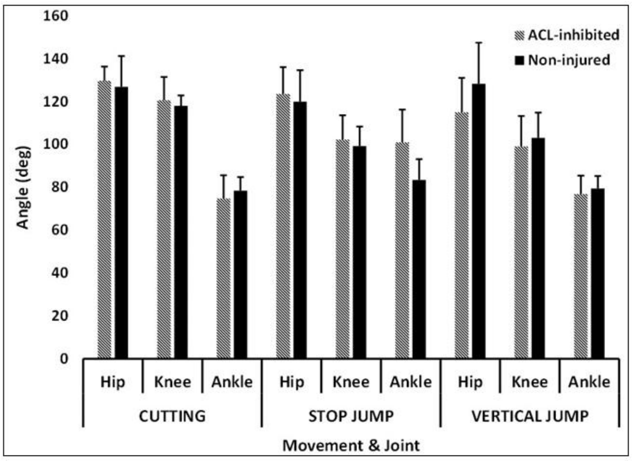

Fig-2: Mean + SD peak hip flexion, knee flexion and ankle dorsiflexion in the three netball skills

The stop jump involved the highest knee angular velocity, particularly in the ACL-inhibited group (mean = 1420.1 deg/s); Fig-3. In the vertical jump, the ACL-inhibited group produced lower knee flexion velocity than the non-injured group.

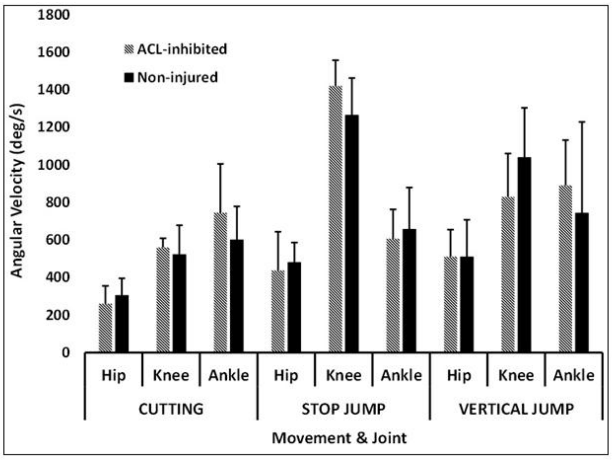

Fig-3: Mean + SD peak flexion velocity in the three netball skills

The highest GRFs occurred in the vertical direction (Fz); Fig-4. In the jumps, the ACL-inhibited group yielded lower Fz (means = 3.0 and 2.1 BW) compared to the non-injured group (means = 3.5 and 3.6 BW). Medio-lateral forces (Fx) were largest in cutting and antero-posterior forces (Fy) were greater in the stop jump.

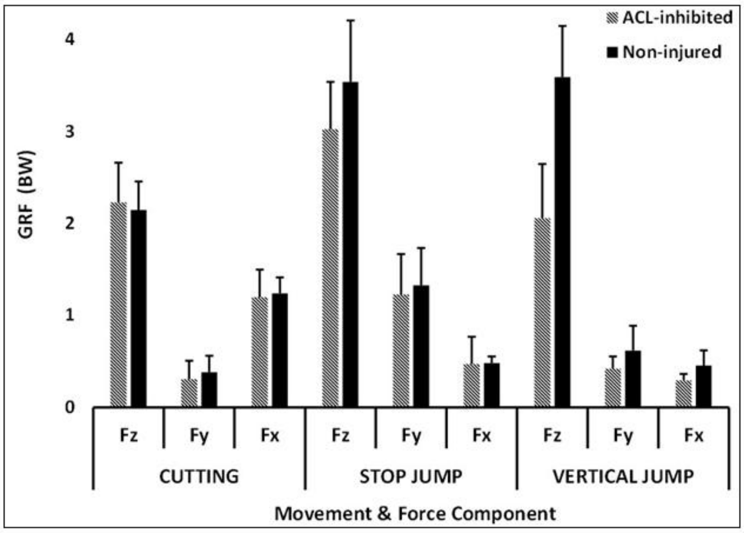

Fig-4: Mean + SD normalised peak GRFs in the three netball skills

The highest loading rates took place in the vertical direction (LRz); Fig-5. In the jumps, the ACL-inhibited group produced lower LRz (means = 112.5 and 63.4 BW/s) compared to the non-injured group (means = 133.0 and 148.1 BW/s). Antero-posterior loading rates (LRy) were higher in the stop jump.

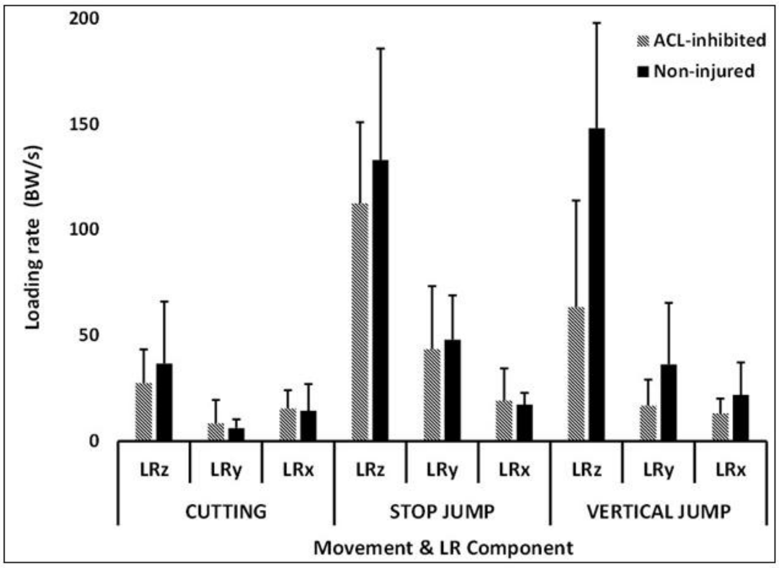

Fig-5: Mean + SD normalised peak loading rate (LR) in the vertical (z), antero-posterior (y) and mediolateral (x) directions

Compressive joint forces incurred in the jumps were smaller in the ACL-inhibited players (Fig-6). Compression was highest at the ankle and least at the hip.

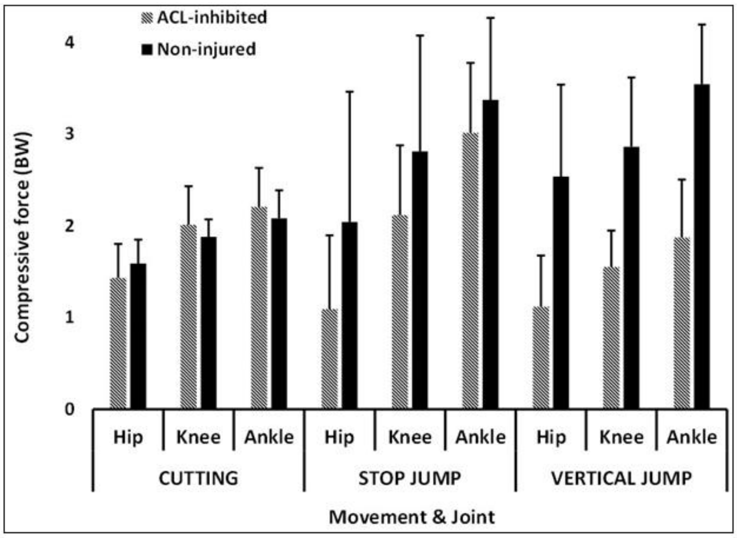

Fig-6: Mean + SD normalised peak compressive forces

The highest shear joint forces occurred in the cutting movement (Fig-7). In cutting, the ACL-inhibited group showed reduced shear at the knee while the non-injured group experienced the larges shear forces at the knee. In the jumps, shear force was highest at the hip and least at the ankle; whereby the ACL-inhibited group underwent lower shear loads.

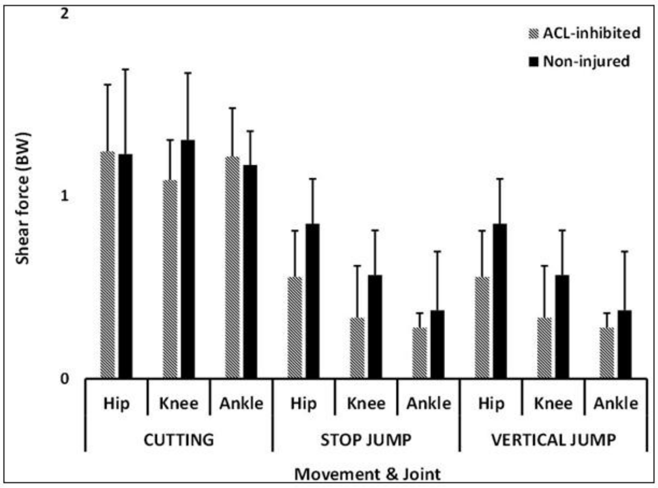

Fig-7: Mean + SD normalised peak shear forces

The movements of the non-injured players were dominated by hip moments (Fig-8). In ACL-inhibited players, moments were lowest at the knee in the cutting manoeuver and the vertical jump.

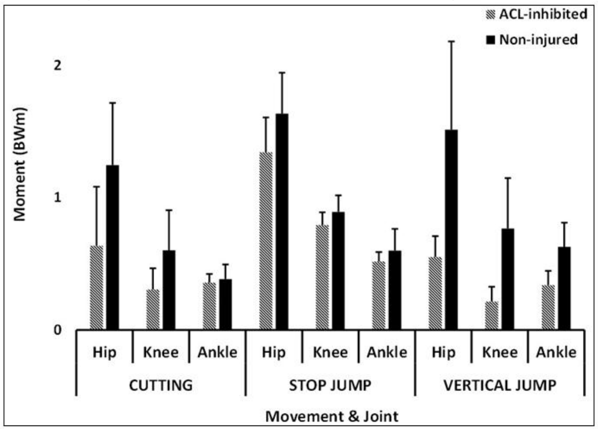

Fig-8: Mean + SD normalised peak joint flexion moments

Table-3 shows within-participant relative percent load distribution between the hip, knee and ankle joints. Relative shear forces at the knee are lower in the ACL-inhibited group in all three netball skills. Relative moments at the knee are lower in the ACL-inhibited group in the two jumps.

Table-3: Percent load distribution

	Cutting			Stop Jump			Vertical Jump		
	Hip	**Knee**	**Ankle**	**Hip**	**Knee**	**Ankle**	**Hip**	**Knee**	**Ankle**
Shear (%)									
ACL-inhibited	35	**31**	34	48	**28**	24	48	**28**	24
Non-injured	33	35	32	47	32	21	47	32	21
Moment (%)									
ACL-inhibited	49	**23**	28	51	30	19	50	**19**	31
Non-injured	56	27	17	52	29	19	52	26	22

Netball skills in which the load distribution at the knee is lower in ACL-inhibited players in bold.

The independent t-tests returned statistically non-significant differences in approach velocity and jump height between the ACL-inhibited and non-injured players (p = 0.22 - 0.71). The scatterplots revealed that GRFs were strongly related to approach velocity and jump height (normalised to participant's height) in the stop jump movement only (Fig. 9). In the cutting movement, the approach to the force plate was at a 45° angle (Fig-1), therefore the approach velocity shown in Fig-9 is the resultant Vx,y velocity of the centre of mass of the participant obtained from Qualisys. The GRFs in Fig-9 are resultant force components Fx,y,z for cutting and resultant Fz,x for the stop jump.

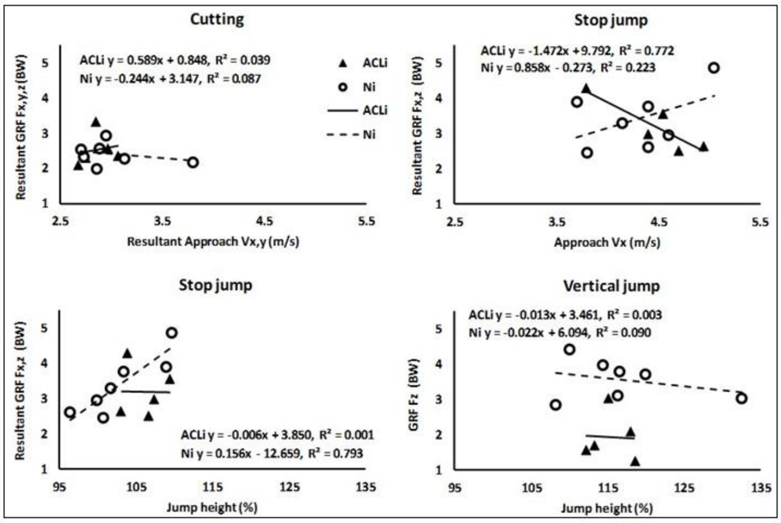

Fig-9: Scatterplots of the covariates approach velocity and normalised jump height vs. normalised GRFs

In the cutting movement, significant effects were found for injury status, lower limb joint, and force component after controlling for the covariate effect of approach velocity (p = 0.001-0.010, η^2 = small 0.074 – large 0.726; Table-4). The Bonferroni-Holm post-hocs revealed significant differences in lower limb joint and force component for all dependent variables, with the exception of shear joint forces.

Table-4: Statistically significant results of the two-way Ancova and Bonferroni-Holm post-hocs with alpha error adjustment ($p < 0.05$). Cutting movement. CV – Approach velocity

Variables	*F ratio*	*df*	*p*	η_p^2	*power*
			Peak angles		
Lower limb joint	119.5	2,29	0.001	0.89	1.00
Hip vs. ankle			0.001		
Knee vs. ankle			0.001		
			Peak angular velocities		
Lower limb joint	19.4	2,29	0.001	0.57	1.00
Hip vs. knee			0.001		

Hip vs. ankle			0.001		
GRFs					
Force component	130.4	2,29	0.001	0.90	1.00
Fx vs. Fy vs. Fz			0.001		
Loading rates					
Force component	6.9	2,29	0.003	.32	.90
Fx vs. Fy			0.003		
Compressive forces					
Lower limb joint	11.0	2,29	0.001	.43	.99
Hip vs. knee			0.010		
Hip vs. ankle			0.001		
Moments					
Injury status	8.5	1,29	0.007	.23	.81
Lower limb joint	12.1	2,29	0.001	.46	.99
Hip vs. knee			0.001		
Hip vs. ankle			0.001		

Ancova analysis of the stop jump netball skill found significant effects for injury status, lower limb joint, and force component after controlling for the effects of approach velocity and jump height (p = 0.001-0.032, η^2 = small 0.107 – large 0.803; Table-5). The post-hocs revealed significant differences in lower limb joint and force component for all dependent variables.

Table-5: Statistically significant results of the two-way Ancova and and Bonferroni-Holm post-hocs with alpha error adjustment (p < 0.05). Stop jump movement. CVs – Approach velocity and approach jump height

Variables	*F ratio*	*df*	*p*	η_p^2	*power*
Peak angles					
Injury status	6.6	1,28	0.016	0.19	0.70
Lower limb joint	19.0	2,28	0.001	0.58	1.00
Hip vs. knee			0.001		
Hip vs. ankle			0.001		
Peak angular velocities					
Lower limb joint	83.8	2,28	0.001	0.86	1.00
Hip vs. knee			0.001		
Knee vs. ankle			0.001		
GRFs					
Force component	140.0	2,28	0.001	0.91	1.00
Fx vs. Fy vs. Fz			0.001		
Loading rates					
Force component	48.7	2,28	0.001	.78	1.00
Fx vs. Fz			0.001		
Fy vs. Fz			0.001		
Shear forces					
Injury status	21.2	1,28	0.001	.43	.99
Lower limb joint	13.0	2,28	0.001	.48	.99
Hip vs. knee			0.008		
Hip vs. ankle			0.001		
Compressive forces					
Injury status	12.3	1,28	0.002	.31	.92

Lower limb joint	9.7	2,28	0.001	.41	.97
Hip vs. knee			0.048		
Hip vs. ankle			0.001		
Moments					
Injury status	6.5	1,28	0.017	.19	.69
Lower limb joint	75.9	2,28	0.001	.84	1.00
Hip vs. knee			0.001		
Hip vs. ankle			0.001		
Knee vs. ankle			0.004		

The Ancova analysis of the vertical jump found significant effects for injury status, lower limb joint, force component, and the interaction injury status * force component after controlling for the effects of the covariate jump height (p = 0.001-0.048, η^2 = small 0.098 – large 0.595; Table-6). The post-hocs showed significant differences in lower limb joint and force component for all dependent variables.

Table-6: Statistically significant results of the two-way Ancova and and Bonferroni-Holm post-hocs with alpha error adjustment ($p < 0.05$). Vertical jump movement. CV – Jump height

Variables	*F ratio*	*df*	*p*	η_p^2	*power*
Peak angles					
Lower limb joint	29.8	2,29	0.001	0.67	1.00
Hip vs. knee			0.003		
Hip vs. ankle			0.001		
Knee vs. ankle			0.001		
Peak angular velocities					
Lower limb joint	6.6	2,29	0.004	0.31	0.88
Hip vs. knee			0.004		
Hip vs. ankle			0.049		
GRFs					
Injury status	28.5	1,29	0.001	0.50	1.00
Force component	22.1	2,29	0.001	0.92	1.00
Injury status * Force component	13.9	2,29	0.001	0.49	1.00
Fx vs. Fz			0.001		
Fy vs. Fz			0.001		
Loading rates					
Injury status	11.9	1,28	0.002	.29	0.92
Force component	25.2	2,28	0.001	.64	1.00
Injury status * Force component	4.5	2,28	0.020	.24	0.72
Fx vs. Fz			0.001		
Fy vs. Fz			0.001		
Shear forces					
Injury status	13.9	1,29	0.001	.32	.95
Lower limb joint	3.9	2,29	0.032	.21	.65
Hip vs. ankle			0.032		
Compressive forces					
Injury status	34.3	1,29	0.001	.54	1.00
Lower limb joint	6.7	2,29	0.004	.32	.88
Hip vs. ankle			0.003		
Moments					

Injury status	27.8	1,29	0.001	.49	1.00
Lower limb joint	10.2	2,29	0.001	.41	0.98
Hip vs. knee			0.001		
Hip vs. ankle			0.002		

DISCUSSION

The ACL-inhibited players showed a joint load distribution that differs to that observed in non-injured players, whereby the percentage of shear forces at the knee are lower in the ACL-inhibited group in all three netball skills and relative moments at the knee are also lower in the ACL-inhibited group in the two jumps (Table-3). This finding suggests the presence of protective compensatory mechanisms that consist predominantly of higher relative shear forces and moments at the hip and ankle than at the knee joint in ACL-inhibited players. Further evidence to support the proposed protective compensatory mechanism theory is shown in Fig-7; in cutting, the ACL-inhibited players showed reduced shear at the knee while the non-injured group experienced the larges shear forces at the knee. Also, in ACL-inhibited players, moments were lowest at the knee in the cutting manoeuver and the vertical jump (Fig-8) providing an indicator of knee joint protection mechanism.

The three netball skills were dominated by hip kinematic action (Fig-2). ACL-inhibited players exhibited greater flexion of the lower limb joints than non-injured players in the stop jump which is a skill that incorporates a forward component of body motion and greater Fy forces and LRy in the antero-posterior direction than the vertical jump (Figs. 4 and 5). This implies greater dissipation of landing forces by means of join flexion in the stop jump by the ACL-inhibited netballers who also showed higher knee angular velocity (Fig-3) suggestive of less joint stiffness at landing. In the jumps, the ACL-inhibited group yielded lower Fz compared to the non-injured group which may be an indicator of re-injury protection mechanism. Medio-lateral forces (Fx) were largest in cutting which render further analysis of internal joint forces and moments in the frontal plane and not only the sagittal plane. In the jumps, the lower LRz in the ACL-inhibited group (means = 112.5 and 63.4 BW/s) compared to the non-injured group (means = 133.0 and 148.1 BW/s; Fig-5) suggest an awareness of the rehabilitated players for the need to protect the knee from high rate loads. Ancova analysis confirmed the presence of significant effects for the three independent variables; injury status, lower limb joint, and force component (Tables 4-6); therefore, the hypothesis that ACL-inhibited players show greater biomechanical loads in the hip and ankle joints to take the strain off the knee was accepted.

The present study identified that ACL-inhibited players demonstrate greater compressive but lower shear forces at the knee during a cutting skill when compared to a healthy control (Figs 6 and 7). The cutting skill requires high levels of abduction and flexion of the knee [23], thus requiring greater stability and control of the knee joint as it is placed further outside the centre of body mass. Silvers and Mandelbaum [1] suggests that the hamstring acts to reinforce the ACL by preventing excessive anterior translation of the tibia. This suggests that ACL-inhibited netballers, may suffer from a deficient quadriceps to hamstring ratio [14, 15], with weakened strength in the hamstring which may explain the greater values of compressive but lower magnitude of shear forces at the knee for the ACL-inhibited players in the cutting skill.

The ankle sustained the largest compressive force and the hip the largest moments throughout all three netball skills in both the ACL-inhibited and non-injured players. Results are supported by previous research [19, 25, 33] that reported the largest sagittal plane moments at the hip. In the cutting skill and the vertical jump, healthy athletes received the lowest torque in the ankle [19, 25, 30] yet ACL-inhibited netballers in the present study demonstrated the lowest relative joint moment at the knee [19, 30]. This suggests that ACL-inhibited netballers utilize an adapted landing strategy that predominantly employs the hip extensor and ankle plantar flexor muscles, and the knee extensor muscles less, as a protective mechanism of the knee [30].

The study endevoured to mimic realistic in-game situations, however most injuries in netball occur under unanticipated conditions, for example when reacting to an unforeseen stimulus or due to physical interaction with other players. Further studies may spontaneously indicate the landing leg or throw the ball into different directions within the controlled environment of the biomechanics laboratory to elicit reactive game conditions. A future study may measure both legs in each participant for a more comprehensive analysis of lower limb loads and interlimb asymmetries.

CONCLUSION

In conclusion, this study found support for a proposed protective compensatory mechanism theory which postulates that ACL-inhibited players appear to utilise protective mechanisms characterised by higher relative shear forces and moments at the hip and ankle than at the knee joint in ACL-inhibited players. In cutting, the ACL-inhibited players showed reduced shear at the knee while the non-injured group experienced the larges shear forces at the knee. Greater and faster flexion of the lower limb joints in the ACL-inhibited netballers is suggestive of less joint stiffness at landing and greater dissipation of landing Fy forces. A suggestion to rectify biomechanical load distribution abnormalities is to implement a special program of functional neuromuscular training for ACL-inhibited netball players from the start of their rehabilitation process until fully healed.

Practical Implications

- The findings have implications for rehabilitation interventions aiming to rectify biomechanical load distribution abnormalities in ACL-inhibited netball players.
- The findings provide insight into abnormal biomechanical loading adaptations that may predispose netball players to re-injury.
- The findings provide reference data for the monitoring of injured player rehabilitation and return to play clearance to guide medical decisions.

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