The role of the foot and a progressive foot muscle strengthening intervention program on common ligament injury mechanism in females participating in court sports.

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Introduction

Court games are characterised by rapid and repetitive short bursts of multiplanar accelerations and decelerations (Chandler, Pinder, Curran, & Gabbett, 2014; Drinkwater, 2008). Abrupt, unanticipated changes of direction put participants of court sports at an increased risk for sustaining non-contact anterior cruciate ligament ruptures (ACL) and lateral ankle sprains (LAS) (Cassell, 2012; Doherty et al., 2014; D. T. Fong, Y. Y. Chan, K. M. Mok, P. Yung, & K. M. Chan, 2009a; McKay, Goldie, Payne, & Oakes, 2001). The rapid, unexpected changes of direction often cause the relatively large explosive ground reaction force (GRF) to not act through the ankle and/or knee joint centres of the stance leg, increasing the risk for lower leg ligament injuries (Beynnon, Renstrom, Alosa, Baumhauer, & Vacek, 2001; B. P. Boden, Torg, Knowles, & Hewett, 2009; Fong, Chan, et al., 2009a; Fong, Ha, Mok, Chan, & Chan, 2012; Gamada, 2014; Gould, Hooper, & Strauss, 2016; Mok et al., 2011; Olsen, Myklebust, Engebretsen, & Bahr, 2004; Stuelcken, Mellifont, Gorman, & Sayers, 2015). Differences in hormonal, anatomical, neuromuscular and biomechanical characteristics between male and female athletes are cited as being responsible for increasing the ligament injury risk for females participating in court sports (Gould, et al., 2016; Shultz et al., 2015).

Injury prevention programs play an increasingly important role in athlete preparation (Joseph and Finch, 2017; Meeuwisse, Tyreman, Hagel, & Emery, 2007). ACL and lateral ankle sprain injury mechanism research site foot mechanics as part of the injury mechanism, but very few intervention programs aim to change foot function directly (Gamada, 2014; Hewett et al., 2005; Shultz, et al., 2015; Willems, Witvrouw, Delbaere, De Cock, & De Clercq, 2005). Footwear research suggest that ankle and knee biomechanics are influenced by barefoot and/or minimalist footwear (Altman and Davis, 2012; Stacoff, Steger, StüSsi, & Reinschmidt, 1996). Several researchers suggest that one potential way to reduce the frequency and severity of these injuries would be to alter the function of foot through strengthening of the intrinsic and extrinsic muscles of the foot (Barry P. Boden, Sheenan, Torg, & Hewett, 2010; Nigg, Baltich, Federolf, Manz, & Nigg, 2017). The aim of this project is therefor to investigate the effect that footwear condition and strengthening specific muscles acting on the will have on the injury mechanism associated with ACL and lateral ankle sprain injuries.

Methods

Participants

Eighteen female court sport athletes (age: 17.4 ±1.49 years; height: 1.68 ± 0.04m; mass: 64.53 ± 9.02kg) gave written consent to take part in this study. All participants were experienced court sport athletes (netball, volleyball and badminton), had sufficient skill to perform vertical jumps and sidestep cuts. All participants were injury and pain free the preceding six months, and had no diagnosed musculoskeletal or neurological condition affecting movement or foot function. Ethical approval was sought and received from Massey University Human Ethics Committee.

Intervention

The participants were randomly allocated to the training group (TG) or the control group (CG). The training group underwent an additional 16-week progressive foot muscle-strengthening program. Foot muscle strengthening exercises was performed three times per week. The researcher regularly supervised the exercise sessions. The exercises chosen aimed to strengthen both the intrinsic and extrinsic muscles acting on the foot.

Data collection

Marker placement

Spherical retro-reflective markers were used to define joint axis and track the motion of the segments of the lower extremities. Markers (diameter 10mm) were placed bilaterally on the anterior superior iliac spine, posterior superior iliac spine, greater trochanter, head of the fibula, tibial tuberosity, and medial and lateral femoral epicondyles. Rigid sets of 4 markers were also placed bilaterally on the lateral side of the thigh and shank. For data capturing in the BFT condition markers (diameter 8mm) were placed on landmark sites according to the multi-segmental foot model as defined by Leardini et al. (2007). In SHD condition markers where placed according to model used by DiCesare et al. (2015). The landmark locations where captured during the static trial for each participant when the participant where in the anatomical position. The global coordination system was used defining the X-axis (sagittal) as orientated medial to lateral, Y-axis (frontal) orientated posterior to anterior and the Z-axis (horizontal) orientated vertically distal to proximal. Kinematic and kinetic data were concurrently collected from the dominant leg by a ten camera (six Oqus 3-series and four Oqus 7-series) Qualisys system (Qualisys, Gothenburg, Sweden) sampling at 200Hz and a force platform (Kistler, 569x DAQ, Winterhur, Switzerland) sampling at 1600Hz.

Experiment protocol

SHD and BFT condition was randomised. Participants underwent a familiarisation period prior to any data collected by running the length of the marked runways. During the familiarisation the participants were guided to achieve the desired approach speed (4.5ms^{-1} ±0.47m.s^{-1}) for the cutting movements in each footwear condition. The jumps were performed after the familiarisation and before the cutting task.

Counter movement jump

Participants were required to perform counter movement vertical jumps (hands on hips) (CMJ) taking off from and landing on both feet on the force platform. The force platform was used to record GRF at take-off and landing during the CMJ. The landing phase was recorded from >20N vertical GRF. Lower limb kinematics were recorded at maximum vertical GRF when landing from the CMJ

Cut

The participants performed 45° (from direction of progression) unanticipated cutting tasks on their dominant leg. Participants were required to perform five successful trials. A trial was deemed successful if the approach run was within 10% of the desired 4.5ms^{-1} approach speed, the force plate was struck with the entire dominant foot and the cut was performed towards the indicated direction. Three electronic timing gates (Smart Speed, Fusion Sport, Queensland, Australia) were placed 5m away and on the opposite side of the force plate. One set of electronic speed gates was placed straight ahead; another timing gate were placed on a 45° angle to the left and another to the right from the approach direction (Figure 1). The SmartSpeed traffic light system were pre-programmed to indicate a random direction (left, right or straight ahead) and flashed 0.7sec after the approach run was initiated .
The approach speed was monitored by an additional photocell timing system (Brower Timing System, USA).

Data processing

Visual 3D^{TM} (v5.0, C-Motion, USA) and MATLAB (R2017a, Mathworks, MA USA) were used to calculate height, knee and ankle frontal plane angles and shank rotational velocity at maximum GRF impact at the time of landing from the CMJ. Kinetic and kinematic data were processed to calculate approach speed, deceleration, stance time, frontal- and sagittal plane knee moment arms and angles, frontal plane ankle moment arms and angles, and shank rotational velocity during the unanticipated cutting task. Kinematic data for the cutting task was recorded at transient impact force (if present) and peak vertical GRF. The vertical ground reaction force at 20N threshold identified the stance phase. All data were time scaled and normalized to 100% of the stance phase. Kinetic and kinematic data were processed in Visual 3D^{TM} (v5.0, C-Motion, USA). Marker trajectories were interpolated for missing signals and smoothed using a sixth-order low-pass Butterworth filter with a 10Hz cut-off frequency. Ground reaction forces were filtered using a sixth-order low-pass Butterworth filter with a cut-off frequency of 12Hz.

Results

Performance variables

Athletes jumped 8% higher shod (23.87±5.00 cm) than barefoot (22.06±5.00cm), F (1, 9) =16.8, $p<.05$. The average approach speed of the 45°cutting task was also significantly quicker shod (4.13±0.34 $m.s^{-1}$) than barefoot (4.04±0.31$m.s^{-1}$), F (1, 9) = 11.31, $p<.05$. In contrast, the stance time during the 45°cutting task was significantly smaller in the barefoot condition (0.21±0.02sec) compared to shod (0.22±0.02sec), F (1, 9) = 20.4, $p<.05$.

Performance was improved with the training intervention in terms of acceleration through the 45°cutting task. An average 29% decrease in acceleration through the stance phase was observed post-intervention (acceleration post-intervention = 1.52±2.09$m.s^2$) compared to pre-intervention (acceleration pre-intervention = 2.14±1.37$m.s^2$), F (1, 9) = 11.19, $p<.05$. On closer inspection it is evident that the intervention training influenced the acceleration performance as the training group had a smaller decrease in acceleration in both barefoot (control group decrease 59%, training group decrease 11%) and shod conditions (control group decrease 44%, training group decreased 17%) compared to the control group.

Kinematic variables

Jump

Kinematics for the dominant lower limb was recorded at the highest vertical ground reaction force during the landing phase of the jump. The ankle inversion angle was larger in the barefoot condition (6.30±5.00°) compared to the shod condition (-1.55±4.61°) which displayed an average eversion angle, F (1, 9) = 135, $p<.0001$. The average ankle inversion angle was also significantly larger (254%) at post-intervention (3.71±4.76°) compared to pre-intervention (1.05±4.81°), F (1, 9) = 6.56, $p<.05$. The average inversion angle increased by 110% from pre-intervention (4.06±5.04°) to post-intervention (8.54±4.88°) in the barefoot condition, while the eversion angle in the shod condition decreased by 43% from pre-intervention (-1.97±4.59°) to post-intervention (-1.13±4.63°), F (1, 9 = 14.43, $p<.05$). The intervention training may have had an effect on the change in the frontal plane angle of the ankle. The training group presented with a larger increase in the barefoot condition (157%) compared to the 76% increased for the control group in the barefoot condition. In the shod condition the training group also had a larger decrease (71%) in the ankle eversion angle compared to the 20% decrease experienced by the control group in the shod condition.

The knee valgus angle displayed a significantly larger increase (115%) from pre-intervention (-2.36±5.02°) to post-intervention (-5.07±5.69°) in the shod condition than the increase (26%) observed in the barefoot condition post-intervention (-2.83±4.56°) compared to pre-intervention (-2.25±4.28°), F (1, 9) = 9.06, $p<.05$.

45° cutting task

Ankle frontal plane

Lower limb kinematics was recorded during the transient and peak vertical GRF incidences during the 45° cutting movement. The external ankle inversion moment arm was significantly larger (175%) in the shod condition compared to barefoot condition at transient (F (1, 9) = 167.7, p<.001) and 334% larger at peak, F (1, 9) = 98.57, p<.0001).

The ankle inversion moment arm at the transient was reduced post-intervention for the shod condition (pre-intervention: 1.90±0.71cm, post-intervention: 1.56±0.75cm), while remaining unchanged for the barefoot condition (pre-intervention: 0.63±0.51cm, post-intervention: 0.63±0.68cm), F (1, 9) = 8.95 p<.05,). The intervention training may have had an influence of the reduction in the ankle inversion moment arm at transient as the training group presented with a larger decrease (37%) in the moment arm post-intervention in the barefoot condition compared to the control group (29%). However, the same reduction in ankle inversion moment arm length was not observed for the shod condition. For peak inversion moment arms, the training group showed a large decrease (128%) post-intervention while barefoot, though remaining relatively unchanged in the shod condition, F (1, 7) = 8.83,p<.05.

In contrast to the external inversion ankle moment arm, the ankle inversion angle was significantly larger in the barefoot condition than the shod condition at both points measured (Transient: F (1, 7) = 63.06, p<.0001, Peak: F (1, 7) = 129.79, p<.001). The ankle inversion angle was also significantly larger post-intervention for both groups at Transient, F (1, 9) = 16.91, p<.05. The influence of the training intervention is not clear as the training group presented with a smaller increase in the ankle inversion angle post-intervention in the barefoot condition compared to the control group while the opposite effect was observed in the shod condition.

Knee frontal plane

The external knee valgus moment arm was significantly larger in the barefoot (-0.218±2.78cm) than in the shod condition which displayed an external varus moment arm (1.66±2.14cm) at Transient, F (1, 9) = 38.78, p<.05. The average external knee valgus moment arm were also significantly larger post-intervention (-0.26±2.92cm) compared to pre-intervention (1.50±2.00cm) at Transient, (F (1, 9) = 9.84, p<.05,). The intervention training seems to have decrease the rate at which the external knee valgus arm increased at post-intervention. At transient the training group had a 217% increase in the valgus moment arm length in the barefoot condition compared to the larger 261% increase experienced by the control group at post-intervention. In the shod condition the training group had a 19% increase in the external varus moment arm length, while the control group had a larger 48% increase at post-intervention.

In contrast to the external frontal plane knee moment arm, barefoot condition had smaller knee valgus angles for both transient and peak, Transient: F (1, 9) = 13.81, p<.05, peak GRF: F (1, 9) = 22.87, p<.05. The athletes displayed a 93% larger valgus angle while shod (-5.82±4.36°) compared to when barefoot (-3.02±4.27°) at transient. At peak the valgus angle in the shod condition (-8.36±4.66°) was 59% larger than barefoot (-5.27±4.06°). The intervention training did not have a clear effect on the knee frontal plane angle.

Shank rotational velocity

The shank internal rotation velocity was significantly slower barefoot post-intervention (pre-intervention: 127.90±108.23°.s^{-1}, post-intervention: 98.10±10.57°.s^{-1}) compared to shod post-intervention (pre-intervention: 124.15±91.36°.s^{-1}, post-intervention: 132.99±103.01°.s^{-1}) at transient, F (1, 9) = 7.2, p<.05.

The training intervention seems to have improved the reduction in internal rotational velocity of the shank post-intervention at transient. Barefoot, the training group had a 38% decrease compared to the 2% decrease in shank internal rotation velocity for the control group and shod, the training group had a 30% decrease while the control group experienced a 62% increase in the internal rotational velocity of the shank. The control group also experienced a significant change at peak where the external rotational velocity observed pre-intervention (-21.54±56.36°.s^{-1}) changed to internal rotation post-intervention (18.85±64.52°.s^{-1}) while the external rotational velocity for the training group remained nearly unchanged (pre-intervention: -47.26±80.88°.s^{-1}, post-intervention: -47.44±79.66°.s^{-1}). While in the shod condition, the control group (pre-intervention: 30.82±68.72°.s^{-1}, post-intervention: -2.49±80.69°.s^{-1}) had a significantly larger increase in external shank rotational velocity post-intervention compared to the training group (pre-intervention: -54.22±105.56°.s^{-1}, post-intervention: -32.70±101.10°.s^{-1}), F (1, 7) = 9.04, $p<.05$.

Table 1: Changes to performance from hands-on-hips vertical jump and 45°cutting movement.

		Barefoot								**Shod**								Significant interactions				
		Control Group (n=10)				**Training Group (n=8)**				**Control Group (n=10)**				**Training Group (n=8)**								
		PreI	**PostI**	**% ↑↓**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		**C**	**S**	**S G**	**S C**	**S G C**
Counter movement jump																						
Jump Height (cm)	Mean	*20.29*	21.44	↑	5%	*23.13*	23.38	↑	1%	*21.24*	23.18	↑	8%	*25.98*	25.05	↓	4%	*				
	SD	±5.14	±5.42			±6.76	±2.66			±5.65	±4.83			±5.99	±4.65							
45°cutting movement																						
Approach Speed (m/s)	Mean	*3.73*	4.35	↑	17%	*3.76*	4.29	↑	14%	*3.88*	4.39	↑	13%	*3.90*	4.37	↑	12%	*	#			
	SD	±0.33	±0.28			±0.25	±0.37			±0.30	±0.34			±0.34	±0.40							
Stance Time (sec)	Mean	*0.23*	0.20	↓	10%	*0.21*	0.19	↓	9%	*0.24*	0.23	↓	7%	*0.22*	0.21	↓	6%	*	*			
	SD	±0.02	±0.02			±0.03	±0.01			±0.02	±0.02			±0.02	±0.02							
Acceleration (m/s^2)	Mean	*1.96*	0.81	↓	59%	*2.65*	2.35	↓	11%	*1.35*	0.76	↓	44%	*2.60*	2.17	↓	17%		*			
	SD	±1.37	±1.83			±1.01	±2.24			±1.33	±1.89			±1.78	±2.39							

*p<.05, #p<.0001; ↑↓=increase/decrease in performance variable; Significant interactions: C = condition, S = session, SvG = session vs group, SvC = session vs condition, SvGvC = session vs group vs condition.

Table 2: Changes to kinematic variables from vertical counter movement jump.

		Barefoot								**Shod**								Significant interactions				
		Control Group (n=10)				**Training Group (n=8)**				**Control Group (n=10)**				**Training Group (n=8)**								
		PreI	**PostI**	**% ↑↓**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		**C**	**S**	**S G**	**S C**	**S G C**
Jump Kinetics (dominant leg)																						
Knee Valgus Angle (°)	Mean	*-2.70*	-2.67	↓	1%	*-1.81*	-2.98	↑	65%	*-2.30*	-5.14	↑	123%	*-2.42*	-5.00	↑	107%				*	
	SD	±3.89	±4.95			±4.66	±4.18			±4.74	±4.61			±5.29	±6.76							
Ankle Inversion Angle (°)	Mean	*4.65*	8.16	↑	76%	*3.48*	8.93	↑	157%	*-2.20*	-1.75	↑	20%	*-1.73*	-0.50	↑	71%	#	*		*	
	SD	±4.20	±5.50			±5.87	±4.26			±4.08	±4.43			±5.29	±6.76							
Shank Rotation Velocity (°/s)	Mean	*42.70*	21.41	↓	50%	*-2.45*	8.98	↑	466%	*32.65*	21.12	↓	35%	*37.00*	33.39	↓	10%					
	SD	±60.23	±72.13			±88.02	±103.95			±63.74	±70.50			±84.10	±71.21							

*p<.05, #p<.0001; ↑↓=increase/decrease in variable value; Significant interactions: C = condition, S = session, G = group, SvG = session vs group, SvC = session vs condition, GvC = group vs condition, SvGvC = session vs group vs condition.

Table 3: Changes to ankle frontal plane kinetics during 45° cutting movement

		Barefoot								**Shod**								Significant interactions				
		Control Group (n=10)				**Training Group (n=8)**				**Control Group (n=10)**				**Training Group (n=8)**								
		PreI	**PostI**	**% ↑↓**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		**C**	**S**	**SG**	**SC**	**SGC**
Ankle external inversion moment arm (cm) (+ = inversion/ - = external)																						
Transient	Mean	*0.68*	0.89	↑	29%	*0.58*	0.37	↓	37%	*1.97*	1.51	↓	23%	*1.83*	1.61	↓	12%	#			*	
	SD	±0.68	±0.74			±0.34	±0.62			±0.72	±0.64			±0.69	±0.86							
Peak	Mean	*0.32*	0.57	↑	78%	*0.25*	-0.07	↓	128%	*1.43*	1.23	↓	14%	*0.97*	1.03	↑	6%	#				*
	SD	±0.66	±0.67			±0.52	±0.64			±0.71	±0.63			±0.65	±0.67							
Ankle inversion angle (◦) (+ = inversion/ - = eversion)																						
Transient	Mean	*19.42*	25.85	↑	33%	*19.86*	25.09	↑	26%	*17.67*	18.22	↑	3%	*16.07*	18.44	↑	15%	*	*			
	SD	±.68	±0.74			±0.34	±0.62			±4.47	±3.86			±3.08	±4.39							
Peak	Mean	*14.99*	19.17	↑	28%	*17.99*	21.35	↑	19%	*10.38*	11.38	↑	10%	*9.78*	13.42	↑	37%	*				
	SD	±4.32	±6.50			±6.80	±4.46			±5.34	±4.73			±5.89	±2.88							

*p<.05, #p<.0001; ↑↓=increase/decrease in variable value; Significant interactions: C = condition, S = session, SG = session vs group, SC = session vs condition, SGC = session vs group vs condition.

Table 4: Changes to knee frontal plane and shank rotational velocity kinematics during 45° cutting movement

		Barefoot								**Shod**								Significant interactions				
		Control Group (n=10)				**Training Group (n=8)**				**Control Group (n=10)**				**Training Group (n=8)**								
		PreI	**PostI**	**% ↑↓**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		***PreI***	**PostI**	**↑↓%**		**C**	**S**	**SG**	**SC**	**SGC**
Knee external valgus moment arm (cm). (+ = varus moment arm/ - = valgus moment arm)																						
Transient	Mean	*1.21*	-1.95	↑	261%	*0.81*	-0.94	↑	217%	*1.85*	0.95	↑	48%	*2.12*	1.71	↑	19%	*	*			
	SD	±2.16	±2.87			±2.37	±3.70			±1.67	±2.46			±1.79	±2.65							
Peak	Mean	*4.49*	3.60	↑	20%	*3.50*	3.25	↑	7%	*4.47*	4.23	↑	5%	*3.80*	3.07	↑	19%					
	SD	±1.13	±2.26			±1.69	±1.84			±1.83	±1.88			±1.98	±1.95							
Knee valgus angle (°). (+ = varus angle/ - = valgus angle)																						
Transient	Mean	*-3.30*	-1.98	↓	40%	*-3.84*	-2.96	↓	23%	*-3.68*	-5.85	↑	59%	*-6.98*	-6.80	↓	3%	*				
	SD	±3.77	±4.08			±4.21	±4.81			±4.34	±4.07			±3.86	±5.16							
Peak	Mean	*-3.64*	-6.22	↑	71%	*-5.79*	-5.44	↓	6%	*-7.19*	-9.54	↑	33%	*-7.40*	-9.34	↑	26%	*				
	SD	±3.94	±4.41			±3.39	±4.50			±5.04	±3.44			±5.58	±4.59							
Shank internal rotation velocity (°/s). (+ = internal rotation/ - = external rotation)																						
Transient	Mean	*102.76*	100.87	↓	2%	*153.03*	95.34	↓	38%	*99.33*	161.13	↑	62%	*148.98*	104.84	↓	30%				*	
	SD	± 99.72	± 111.62			± 116.74	± 99.53			± 87.84	± 106.56			± 94.88	± 99.46							
Peak	Mean	*-21.54*	18.85	↑	188%	*-47.26*	-47.44	↓	0.4%	*30.81*	-2.49	↓	108%	*-54.22*	-32.70	↑	40%					*
	SD	± 56.35	± 64.52			± 80.88	± 79.66			± 68.72	± 80.69			± 105.56	± 101.10							

*p<.05, #p<.0001; ↑↓=increase/decrease in variable value; Significant interactions: C = condition, S = session, SG = session vs group, SC = session vs condition, SGC = session vs group vs condition.

Discussion

Performance

There is no clear recommendation with regards to footwear condition to enhance athletic performance of females during court sport activities. The CMJ height, and approach velocity of the cutting tasks was significantly improved when shod compared to barefoot. In contrast, the stance time and acceleration through the stance time of the 45° cutting task was improved when barefoot. General athletic training and condition had a larger effect on approach velocity than on the 45° cutting task than footwear condition as both groups displayed better post-intervention velocities in both footwear conditions. It is interesting to note that although both groups had improved their approach running velocity the acceleration through the stance phase of the cutting task was reduced for both groups at the pre-intervention test. However, the athletes that underwent the strength training intervention had a smaller loss in acceleration in both footwear conditions possibly indicating the benefit of strengthening the muscles acting on the foot.

Kinematic outcome variables

The kinematic outcome variables recorded during the CMJ as they relate to ACL and LAS injuries were mostly reduced when performed barefoot. When landing barefoot from a jump the knee valgus angle and the internal rotational velocity of the shank were significantly smaller than when landing shod possibly reducing ACL injury risk when barefoot. Ankle eversion is associated with larger knee valgus angles. It is therefore not surprising that larger ankle eversion angles was observed in the shod condition compared to barefoot during CMJ landing (Hewett, et al., 2005). In contrast, larger inversion angles was observed during barefoot landing, possibly increasing the risk for LAS injury during CMJ landing. It can therefore be inferred that the risk to ACL injuries may be reduced when performing CMJ barefoot or in a shoe that mimics the barefoot condition. Although, there might be an increased risk for LAS injury when performing CMJ barefoot compared to shod.

During the 45° cutting movement, the external ankle inversion moment arm was closer to the ankle joint centres when performed barefoot compared to shod possibly decreasing the risk for LAS injury. Although, when shod a shorter external ankle inversion moment arm was observed at transient during post-intervention. However, the resultant GRF was still closer to the ankle joint centre in the barefoot condition maintaining a reduced risk for LAS in the barefoot condition.

The transient and peak ankle inversion angles was larger barefoot and may therefore increase the risk for LAS. However, the increased moment arm length observed shod holds the greater risk for LAS incidence (D. T. Fong, Y. Y. Chan, K. M. Mok, P. S. Yung, & K. M. Chan, 2009b; Fong et al., 2009) . Thus performing 45° cutting movement barefoot or in a barefoot type shoe may decrease the risk for LAS injury. The training intervention may have further decreased the risk for LAS at transient as the external ankle inversion moment arm was smaller for the training group compared to the control group in both barefoot and shod conditions.

In the barefoot condition the average transient external knee valgus moment arm was significantly larger than shod. However, the transient length of the valgus moment arm observed barefoot was smaller than the valgus moment arm in the shod condition. Thus, putting the resultant GRF closer to the knee joint centre. Similarly the peak external valgus moment arm barefoot was shorter than the moment arm in the shod condition. The shorter moment in the barefoot condition decreases the risk for ACL injury at both time points. Furthermore, the knee valgus angles were also smaller in the barefoot condition at both time points, also decreasing ACL injury risk.

The intervention training seems to have limited the increase in the external knee frontal plane moment arm length and also decreased the rotational velocity of the shank, decreasing ACL injury risk further. The rotational velocity of the shank was reduced in both footwear conditions as well when comparing pre-intervention to post-intervention results at transient. The effect of the intervention training and footwear condition on the rotational velocity of the shank was less clear at peak.

Table 5. Outcome variables best result in relation to footwear condition

Barefoot (or Minimalist)	**Shod**
Jump	
	Greater Jump Height
Smaller knee valgus angle and shank rotational velocity, reduces risk of ACL injury	Smaller ankle inversion angle, reduces LAS risk
45°cutting movement	
Shorter Stance time increases performance	Faster Approach Speed increases performance
Smaller decrease in Acceleration through stance increases performance	
Ankle frontal plane moment arm closer to ankle joint centre at Transient and Peak - decrease risk for LAS	Smaller ankle inversion angle – decrease risk for LAS
Knee frontal plane moment arm closer to knee joint centre – decreases risk for ACL injury	
Smaller Knee valgus angle – decreases risk for ACL injury	
Slower shank rotational velocity – decreases risk for ACL injury	

Conclusion

ACL and LAS injury risk was reduced when CMJ and 45° cutting tasks was performed barefoot. The risk to ACL and LAS injury seems to be further reduced for the athletes who performed the strengthening exercises. Strengthening the muscles acting on the foot and performing court sport activities barefoot or in a barefoot type shoe may therefore be recommended to females. No clear recommendation can be made about footwear regards to performance enhancement as results where varied. Equally, strengthening the muscles acting on the foot had no clear statistically significant regards to performance enhancement.

It should be made clear that although this experiment may have found a reduced risk for ACL and LAS in barefoot or barefoot type shoe wear for females participating in court sport, the tasks were conducted in a controlled laboratory. Research is needed in a 'real world' setting to be able to obtain conclusive evidence regarding the ability to reduce injury risk without causing other injury. Prudent care should thus be taken when introducing barefoot/ minimalist shoe wear into court sport activities. Should an athlete decide to take advantage of the benefits associated with adopting barefoot/ minimalist shoe play and/or training, a gradual foot wear change complimented by strength training for the muscles acting on the foot is strongly recommended.

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