A SYSTEMATIC REVIEW OF LOWER LIMB ASYMMETRY AFTER ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTION IN ADOLESCENT ATHLETES

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Anterior cruciate ligament (ACL) rupture is a common athletic injury in adolescents which typically requires surgery to repair the injured ACL. Despite considerable efforts to improve outcomes, secondary ACL injury is common in athletes who return to sport. One of the main risk factors for secondary ACL injury is asymmetry in landing mechanics. The aim of this systematic review was to identify the common biomechanical asymmetries after ACL reconstruction in adolescents during landing. Sources were identified through searching databases using relevant search terms. Study titles and abstracts were screened using inclusion criteria which resulted in 13 articles being selected for further analysis. The methodological quality of each study was assessed independently by three reviewers. Asymmetry was more commonly identified in kinetic variables than kinematic variables. The most common asymmetries identified were peak knee extension moment and peak vertical GRF, both of which were frequently shown to be significantly lower in the surgical limb compared to the uninjured limb. These findings suggest that return to sport criteria following ACL reconstruction should incorporate analysis of the asymmetry in loading experienced by each limb rather than examining movement patterns alone. **KEYWORDS:** ACL injury, landing, biomechanics.

INTRODUCTION: It has been reported that between 250,000 and 300,000 ACL injuries occur annually (Prodromos et al., 2007) the majority of which (approximately 72%) occur in non-contact situations. As a result, the incidence of ACL injury is particularly high for sports characterised by a high frequency of landing, side-stepping/cutting or change of directions. Most athletes who aim to return to competition after ACL injury choose to have surgery to repair the ligament. Despite advances in surgical and rehabilitation practices, the prevalence of secondary ACL injury is very high. Paterno et al. (2012) found that for adolescent athletes (n = 78) who underwent ACL reconstruction, 30% had a subsequent ACL injury within two years of returning to sport. Asymmetry in landing mechanics has been proposed as a risk factor for secondary ACL injury (Paterno et al., 2010). This asymmetry is likely due to reduced function of the surgical limb which will likely result in a compensatory strategy of increasing the loading of the non-surgical limb which places both the surgical and non-surgical limb at an increased risk of a secondary injury. During adolescence, the musculoskeletal system alters structure and function which has been shown to result in altered landing mechanics (Hewett et al., 2006). ACL reconstruction and resulting asymmetry in lower limb mechanics may therefore have a more profound effect on young athletes. The aim of this systematic review was to identify the common biomechanical asymmetries reported after ACL reconstruction in adolescents during landing movements. This paper presents part of a larger study (Hughes, Musco, Caine, & Howe, In press).

METHODS: Relevant sources were identified through searching SPORTDiscus, CINAHL, Scopus and PubMED electronic databases. Databases were searched from their first reported date of January 1966 to January 2019. The following search terms were used: Asymmetry OR symmetry AND landing AND biomechanics OR kinematics OR kinetics. Articles not written in English were excluded, along with reviews, meta analyses, non-peer reviewed sources and abstracts unaccompanied by a full-text journal article. A total of 164 articles were identified.

Article data (including authors, title, abstract, journal) were downloaded to RefWorks (ProQuest®, Ann Arbor, Michigan, USA) citation management software where duplicate citations were deleted. This reduced the number of citations to 85 articles. Following this, inclusion criteria were applied through reviewing article titles and abstracts. These criteria required studies to include human participants who had ACL reconstruction surgery and were

adolescents (mean age above 11 and below 18). The study had to include one or more kinetic or kinematic measure of asymmetry which compared between surgical and non-surgical limbs. Lastly, the task performed was required to be either a bilateral or unilateral landing manoeuvre which included single leg vertical jump landing, single leg vertical drop landing, double leg vertical drop jump landing and vertical stop-jump landing. For drop landings, drop heights ranged between 31 cm and 40 cm with the first landing being used for analysis. Two independent reviewers assessed all articles considered for inclusion with any disagreements resolved through verbal discussion after all articles had been reviewed. Once inclusion criteria had been applied, a total of 12 papers were selected. The reference lists of each paper were then inspected to identify further studies which found one further study to be included, bringing the total research papers to be included in this systematic review to 13. Three reviewers independently assessed each study's methodological quality using the Downs and Black (1998) revised checklist where 14 relevant criteria were included. A study which scored ≤8 was considered low quality, a study which scored 9-10 was moderate quality and a study which scored ≥11 was considered high quality. Disagreements were again resolved by a consensus meeting.

RESULTS: For the studies assessed, 5 scored high quality, 7 scored moderate quality and only one study scored low quality (Table 1). The average score was 10.2 out of 14, suggesting moderate quality overall.

Most studies only examined asymmetries in the sagittal plane, with only three studies examining variables in all three planes of motion. In the sagittal plane, kinematic and kinetic joint variables were examined a total of 61 times across 10 studies, compared to only 14 times across 5 studies for the frontal plane and 7 times across 4 studies for the transverse plane. Significant differences between surgical and non-surgical limbs were commonly observed in the sagittal plane, where 29% (9/31 included data points) of times significant differences were observed for sagittal plane kinematics and 70% (21/30 included data points) of the time significant differences were observed for sagittal plane kinetics. Very few kinematic variables were found to be significantly different between surgical and non-surgical limbs in the frontal and transverse planes (only 1 significant difference in 13 variables measured across 5 studies) but for kinetic measures in the frontal and transverse planes, 6 significant differences were observed for only 8 variables measured across 4 studies (Table 1).

The most commonly measured variable was peak vertical GRF, which was measured in 10 out of the 13 studies. It was also the variable which was most commonly found to be significantly different between limbs, with 9 studies finding a significantly reduced vertical GRF for the surgical limb compared to the non-surgical limb. The only study which measured peak vertical GRF and did not find a significant difference between limbs utilised a single limb landing task, whereas the other 9 studies which did find a significant difference between limbs used double limb landing tasks. The second most commonly measured variable to assess asymmetry was peak knee extension moment, which was measured in 7 of the 13 studies and found to be significantly reduced in the surgical limb compared to the non-surgical limb in 6 of those 7 occasions, all of which employed a double limb landing task (Table 1).

DISCUSSION: The most commonly measured variables and the variables where asymmetry between surgical and non-surgical limbs was most frequently identified were for sagittal plane knee kinetics and vertical GRF. This is supported by Lepley and Kuenze (2018) who also found significant asymmetry in these variables for ACL reconstructed adults during landing. In all cases where significant kinetic asymmetry was identified, the loading of the surgical limb was found to be significantly lower than the non-surgical limb. It should be noted that the only study which measured peak vertical GRF and did not find the surgical limb to be significantly lower than the non-surgical limb used a single leg landing task where the option of unloading the surgical limb through placing additional load on the non-surgical limb is not possible. This

suggests that both double and single limb tasks should be used when monitoring asymmetries during rehabilitation following ACL reconstruction.

Generally, studies reported significant differences far more commonly in kinetic variables rather than kinematic variables, a finding supported by Lepley and Kuenze (2018). Whilst some studies reported significant differences for sagittal plane kinematics, only once was a frontal or transverse plane kinematic variable reported to be significant different between limbs in the 13 cases of these variables being measured. Frontal and transverse plane kinematic variables have been strongly implicated as risk factors for primary ACL injury (Paterno et al., 2010) but these variables may not be as strong a risk factor for secondary injury. It is however worth noting that these findings only relate to asymmetry between surgical and non-surgical limbs and not to comparisons between injured and healthy individuals or between pre and post ACL injury. While not commonly measured, those studies that did measure kinetic variables in the frontal and transverse planes commonly reported significant asymmetry in those variables. This highlights that further investigation is required for frontal and transverse plane kinetic asymmetries between surgical and non-surgical limbs.

Table 1: Summary of variables measured to assess biomechanical asymmetry in each study.

		Butler et al. (2016)	Butler et al. (2014)	Dai et al. (2014)	Ithurburn et al. (2017)	Mueske et al. (2018a)	Mueske et al. (2018b)	Myer et al. (2012)	Paterno et al. (2010)	Paterno et al. (2011)	Renner et al. (2018)	Schmitt at al. (2015)	Schneider et al. (2017)	Wren et al. (2018)
Study quality score	Out of 14 points (≥11 = high, 10-9 = moderate, ≤8 = low)	10	10	10	10	11	11	10	6	12	11	12	9	10
Landing type		Double limb stop-jump	Double limb stop-jump	Double limb stop-jump	Single limb vertical drop	Double limb vertical drop-jump	Double limb vertical drop-jump	Single limb vertical hop	Double limb vertical drop-jump	Double limb vertical drop-jump	Double limb stop-jump	Double limb vertical drop-jump	Single limb vertical drop	Single limb forward hop
Sagittal plane kinematics	Hip angle at IC													
	Hip ROM													
	Peak hip angle	↑												
	Knee angle at IC													
	Knee ROM													
	Peak knee angle					↓					↓			↓
	Peak knee angular velocity													
	Knee flexion angular velocity at IC													
	Knee angle at peak angular velocity													
	Ankle angle at IC	↓												↑
	Peak ankle angle					↓	↓							
Frontal plane kinematics	Hip angle at IC													
	Peak hip angle													↑
	Mean hip angle													
	Knee angle at IC													
	Knee ROM													
	Peak knee angle													
	Mean knee angle													
Transverse plane kinematics	Hip angle at IC													
	Peak hip angle													
	Mean hip angle													
	Knee angle at IC													
	Peak knee angle													
Sagittal plane kinetics	Peak hip moment													
	Mean hip moment													
	Hip energy absorption													
	Peak knee moment	↓	↓	↓			↓				↓	↓		
	Mean knee moment			↓		↓								↓
	Knee moment at peak angular velocity		↓											
	Knee energy absorption			↓		↓	↓							↓
	Peak ankle moment	↓												
	Mean ankle moment					↓	↓							↑
	Ankle energy absorption					↓	↓							
Frontal plane kinetics	Peak hip moment													
	Mean hip moment					↑	↑							
	Peak knee moment													
	Mean knee moment					↑	↑							↓
Transverse plane kinetics	Peak hip moment													
	Mean hip moment					↑								
	Peak knee moment													
Ground reaction force	Peak vertical	↓	↓	↓		↓	↓	↓		↓	↓	↓		
	Peak posterior			↓							↓			
	Loading rate			↓							↓	↓		
	Vertical impulse										↓			
	Anteroposterior impulse													
Knee joint stiffness	Peak										↓		↓	

variable was measured but no significant difference reported between surgical and non-surgical limbs.
↑ significantly greater in the surgical limb.
↓ significantly less in the surgical limb.

Overall, the finding that asymmetries are more commonly identified in kinetic variables rather than kinematic variables strongly supports the notion that return to play criteria for athletes following ACL reconstruction require some assessment of the asymmetry in loading between limbs and should not rely on assessing symmetry in movement patterns alone. Current criteria typically include consideration of time since surgery, asymmetry between surgical and non-surgical limbs in both strength and hop distance, as well as qualitative movement analysis during sporting tasks. The findings of this review show that some athletes are likely to exhibit symmetrical movement patterns between limbs whilst still exhibiting potentially dangerous asymmetries in loading between limbs. Therefore, if return to play criteria only include kinematic description of asymmetry between surgical and non-surgical limbs, it is likely that many athletes would be prematurely cleared to return to competition and subsequently risk secondary ACL injury. Future research should consider the development of improved return to

play criteria after ACL reconstruction which includes affordable techniques for analysing lower limb loading during landing.

CONCLUSION: For the studies included in this systematic review, significant asymmetries between surgical and non-surgical limbs were more frequently identified in kinetic variables than kinematics variables. The most common significant asymmetries reported were peak knee extension moment and peak vertical GRF during double limb landing, both of which were frequently shown to be significantly lower in the surgical limb compared to the uninjured limb. In most cases, lower limb kinematics did not present significant asymmetry between limbs. Our findings suggest that return to sport criteria following ACL reconstruction should incorporate analysis of the asymmetry in loading experienced by each limb, rather than examining movement patterns alone.

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