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Title: The Effect of Fatigue on Phase Specific Countermovement Jump Asymmetries in ACL-R and Non-injured Rugby Union Players

Running Head: Fatigue effects on CMJ asymmetries post ACL-R

**Abstract**

Return to play (RTP) criteria and analysis of neuromuscular asymmetries should be evaluated and monitored to prevent high re-rupture rates in individuals that have undergone ACL reconstruction (ACL-R). This study investigated asymmetries between two groups of male rugby players (ACL-R and non-injured) in bilateral and unilateral countermovement jump (CMJ) performance pre and post-match play. Three countermovement jumps (CMJs) were performed pre, post 30 minutes and 48 hours post game play. Force plates assessed vertical ground reaction forces and kinetic CMJ metrics, whilst sagittal lower limb kinematics were recorded. Global position systems were used to measure match-running variables to quantify workload. No significant difference existed in CMJ phase specific asymmetries between groups and also no time and jump interaction (p> 0.05). Significant time effect changes occurred in ankle, knee and hip flexion angles, highlighting an altered movement strategy. A significant difference (p=0.004) in total distance covered was observed between the population groups (non-injured 6260.1 ± 524.2 m and ACL-R 4919.6 ± 771.7 m). No significant group differences existed between athletes that have previously undergone ACL-R and non-injured individuals for neuromuscular asymmetry values. This highlights the importance of individualised testing and tailored RTP criteria due to different positional and physiological demands.

Key Words – Jump Performance, Symmetry, Rugby Union, Neuromuscular Fatigue, Imbalances

**Introduction**

High force and high velocity movements such as running, cutting, jumping and tackling tasks in rugby union are expressed in an unpredictable fashion under fatigue potentially leading to injurious events.  In a review of546 rugby union players from the English premiership, knee injuries were found to be the second most common injury equating to 12% of total injuries with 4.3% of this value representative of Anterior Cruciate (ACL) injury incidence1. Placing incidence of ACL injuries per 1000 match play hours, at 0.421. ACL injuries lead to the greater time absent from competition than any other knee injury with a mean absence of 271 days1. In addition to this, ACL re-rupture rates are high in individuals involved in competitive sport with highest values occurring in a period of between 6-12 months2,3.

Due to these high re-injury rates it is important not to solely utilise time scale-based return to play (RTP) that has no relation to functional quantitative outcome measures4. However, an understanding of which exact outcome measures are indicative of increased risk of re-injury still need further investigation. Current literature suggests risk factors for repeat injury include poor neuromuscular control and ability to absorb external energy during lower body multi-joint dynamic movements5,6. Objective criteria with strength symmetry and hop tests (only quantifying distance) have been utilised as minimal standard criteria due to ease of administration4. Nonetheless, these alone may give no indication of jumping related phase specific neuromuscular deficiencies. More advanced analysis for high-level athletes returning to elite sports performance is required. Rigorous neuromuscular testing is recommended by performance and medical practitioners for clearance in return to unrestricted activities to ensure the athletes pre-injury physiological and biomechanical qualities are restored to ensure safe RTP3.

Bilateral and unilateral counter-movement jump (CMJ) testing can provide an overview of neuromuscular function for the individual athlete and also used for acute and chronic fatigue monitoring during RTP preparation7. Dual plate systems can evaluate functional limb asymmetries after injury through the eccentric and concentric movement phases. This has been utilised to prospectively identify athletes that may be at risk of injury8. Unilateral jumping tasks have been favoured due to an associated increase level of ecological validity related to the nature of the movement patterns in teamsports9. Also due to the instability of unilateral jumping there is an enhanced sensitivity for detecting true asymmetries10. However, reliability of unilateral jumps are questioned due to the need for balance and support to be maintained, which may lead to negative effects on velocity and force production when analysing strength deficits11. Thus, a combination of bilateral and unliteral testing may be favourable. Additionally, this modality of testing may also be used to analyse post-operative performance after RTP criteria have been achieved. The strong association between CMJ measures and performance in power athletes may be utilised to highlight neuromuscular deficits before their return to competitive match play.

Re-injury risk in ACL-R athletes have found to be increased if inter limb asymmetries are not addressed2,12. An evaluation of jumping tasks has demonstrated that ground reaction force (GRF) differences between limbs have numerous effects not only on re-injury but also on sport specific performance9,13,14. Although 10% is seen as the critical asymmetry value, other studies have associated values larger than 15% asymmetry to be related to increased injury incidence12,14,15. Vertical GRF asymmetries during the eccentric phase, indicated a potential compensatory movement strategy and avoidance pattern for the injured limb in the form of increased loading through the healthy limb16. As well as decreasing single-bout performance, altered leg dominance as a result of injury is likely to decrease movement efficiency and elicit early onset of fatigue17. This highlights the importance of measurement of movement efficiency alongside kinetic variables in the prediction of performance and injury risk in the later stages of a match. Commonly reported components of a CMJ consist of peak GRF, velocity, jump height and power18. However, these variables do not give insight into phase specific qualities18. Important phase specific neuromuscular variables such as eccentric/concentric forces, impulse and durations allow coaches and practitioners to formulate a better understanding of the mechanisms in which force is derived or dissipated19,20. Improvement in eccentric force producing qualities can lead to increased muscle tension for force absorption leading to higher values of muscle stiffness, subsequently protecting ligaments and joint structures from injury21,22. Due to limited research on eccentric measures in jump performance in rugby union it is important to investigate these variables and gain a better understanding of whether asymmetries in these variables present post ACL-R.

These asymmetries can occur as a consequence of altered neuromuscular control involving muscle contractile force and activation time alterations when fatigue is present23. Montgomery et al15 found that 47% of non-contact injuries and 42% of all other injuries occurred in the last 20 minutes of the match. Repeated stretch-shortening movements such as sprinting, tackling, cutting and jumping have been shown to elicit fatigue in rugby union athletes24. Gathercole et al20 found changes in neuromuscular function during jumps involving stretch shortening cycle (SSC) actions with differences displayed in 67% of measured variables post fatigue protocol. Interestingly the jump variables returned to baseline levels 24-hours later, but a secondary decrease in function (eccentric/concentric durations,FT/CT and time to peak force) occurred 72-hours post-exercise. This highlights the biphasic recovery pattern after SSC fatigue. With most Rugby Union athletes returning to training 48 hours post- match, this could impact injury risk and also the level of performance within training.

Previous literature has highlighted the use of CMJ as a method of screening limb symmetry, a vital component in the construction of RTP criteria post ACL-R8. The effect of fatigue on kinetic asymmetries may also be greater in athletes post ACL-R 10,11,25. Therefore, phase-specific screening is vital to effectively identify performance deficits that may highlight increased risk of re-injury. Currently, there is very little evidence in neuromuscular function of elite rugby union players with a history of ACL-R. This information is crucial to improve the scientifically guided RTP criteria post ACL-R and ensure safety for return to sport26. Therefore, this study aimed to investigate if asymmetries in neuromuscular variables exist between ACL-R and non-injured rugby union athletes using the CMJ. It also investigated whether match fatigue impacted these neuromuscular variables and led to a change in asymmetry values 30 minutes and 48 hours post-match. It was hypothesised that larger asymmetries would exist in CMJ variables in the ACL-R group over the non-injured group and that these asymmetries would be greater 48 hours post-game under conditions of fatigue.

**Method**

The design of this current study was a repeated measures cohort study to investigate asymmetries in jump metrics between non-ACLR and ACLR elite rugby player’s pre and post-match play. Participants were assessed using the bilateral and unilateral CMJ before the warm-up and again 30 minutes and 48 hours post-game where kinetic variables were analysed to assess for inter-limb asymmetries.

Participants

Fourteen male professional rugby players, competing in either the English premiership, championship or national league one were recruited for this study. Details of these participants can be seen in Table 1. Ethical approval for this study was provided by the St Mary’s University Ethics Committee.

\*\*\*\*\*\*Insert Table 1 here\*\*\*\*\*

An a priori sample size calculation (Gpower 3.0.10) using eccentric impulse results reported by Jordan et al18highlighted to achieve a power of 0.8 a total sample size of n=12 was required (6 in each group). ACL-R participants must have had an ACL reconstruction within the last 24 months. Participants with bone-patellar tendon-bone autograft and hamstring autograft were included within this study. Participants with an allograft were within the inclusion criteria, however no participants underwent this method of reconstruction. Participants were also included if they sustained secondary injuries associated with primaryACL such as meniscal, articular cartilage and medial collateral ligament damage27. Participants were partaking in similar training routines including 5-8 training sessions (3 gym based and 2-3 rugby) and a weekly match. Training must have included bilateral and unilateral CMJ Jump movements in the 2 weeks prior for familiarisation of movement28. To ensure this criterion, programming information was provided to the principle research by the Strength and Conditioning Coach of each athlete. If these were not included within the current programme, the Strength and Conditioning Coach were asked to include them for the 2 weeks prior to testing. All ACL-R Participants had been deemed ready to play by their club physio and surgeon. Prior to testing, participants were also asked to avoid any strenuous activity for 24h beforehand.

If any symptoms of lumbar spine or patellofemoral knee pain, previous knee ligament, meniscal or cartilage injury on the non-operated leg and a history of any further lower body injuries that required surgery in the last twenty-four months then participants will be excluded from this study. If participants did not undergo the required amount and type of training sessions within a training week then they were excluded within the study. Exclusion will also take place if the club physio has not deemed a player fit to play.

Jump Protocol

The CMJ testing procedure was performed pre-warm-up and again post-match within 30 minutes and 48 hours. Prior to data collection, reflective markers for 2D analysis were placed on the following anatomical landmarks: 5th metatarsal, lateral malleoli, lateral condyle, greater trochanter and mid deltoid. Participants performed a 10-minute standardised warm up consisting of 5 minutes on a stationary bike, 3 minutes of self-selected mobility work, 10 squats, 10 lunges and 1 submaximal practice jump. The bike was performed at a self-selected level of a rate of perceived exertion (RPE) value of 4. Three bilateral were performed first followed by six unilateral CMJ (3 on each leg) at each of the three assigned testing times. The participants were asked to stand motionless on the platforms and a countdown of 3 seconds began to achieve a baseline force which represented body mass. After achieving a stationary baseline force, the participants were instructed to jump maximally as high and as fast as possible on each jump. Hands were placed on the hips to prevent the swinging arm having an impact on jump performance29. The depths of each CMJ were self-selected. This process was then repeated for all three bilateral CMJ and six of the unilateral CMJ with bilateral jumps always performed first, followed by unilateral right then left. One minute of rest between jumps was provided

The CMJ was filmed using a 2D camera (Panasonic HCV210 HD camcorder) and analysed using Kinovea software (Version 0:8:15) to determine ankle, knee and hip flexion angles. The camera was set up perpendicular to the sagittal plane and positioned using triangulation to ensure the camera was positioned evenly. It was then adjusted for pan, roll and tilt with a shutter speed of 1/1000. The flexion angles of each CMJ jump were taken. This process was then repeated 30 min, 24 hours and 48 hours post-match. CMJs were performed on a dual force plate system (Model No: PS 2141; Pasco Roseville, CA, USA) with vertical ground reaction force (Fz) sampled at 1000-Hz. The raw vertical force-time data was exported as a text file for each jump trial from sparkview software and analysed using a Microsoft Excel customised spread sheet. Reliability in intraday CMJ variables has been evaluated in a previous study, where 16 of the22 variables analysed exhibited coefficient of variation (CV) values of <5%8.

Data Analysis

Body mass was  derived from a 3 second silent period whereby the first 0.6 seconds of vertical force (Fz) data was averaged. The onset of movement was identified as the point when vertical force had reduced decreased by five times the standard deviation of body weight30. COM velocity was calculated by time integration of the instantaneous acceleration (force divided by the mass).  Displacement was calculated by time integration from the instantaneous velocity.

The eccentric phase was defined as the point from lowest centre of mass (COM) velocity to lowest displacement (deepest COM position) whereby the concentric phase was defined from the lowest displacement row to take off (first value below 10N)8. Phase distinction can be seen below in Figure 1.

\*\*\*\*\*\*Insert Figure 1 here\*\*\*\*\*\*

The Jump variables analysed have previously been investigated by Gathercole et al18 with eccentric variables of primary focus. These variables can be seen below in table 2.

\*\*\*\*\*\*Insert Table 2 here\*\*\*\*\*\*

An asymmetry index calculation was used to calculate the asymmetry value differences between rightand left limb, ACL-R and non-ACL-R limb and to maintain directionality8. A positive number  indicates right limb or ACL-R dominance and a negative number will indicate left limb or Non-ACL-R dominance. This allows for clear differentiation between limbs.

Match play was used as the fatiguing bout of exercise for all participants although the match in which they participated was varied. Global positioning system (GPS) data was collected for the game that each participant performed their jump testing procedure either side of and utilised to measure external workload of each participant. The GPS system used was the FieldWiz EN A8.ai with a sampling rate was 10Hz. The six variables calculated were total distance, meters per minute, high-speed meters (5 m/s) and accelerations and decelerations (3,4 and 5 m/s/s). These data sets were used to compare workloads of individuals through the match and to ensure that workloads were of similar values when group comparisons were made. The threshold of 5m/s for high speed meters was in line with guidelines of movement’s demands in elite rugby union players31.  A rate of perceived exertion (RPE) scale32 was also collected from each participant pre-game, at half time and immediately post-game as a measure of perceived exertion of the game (Appendix 1). This is to give an idea of internal workload for each participant and how tough they perceived that game to be.

Statistical Analysis

All force data was initially calculated in excel and analysed in SPSS (SPSS Inc., IL, USA). Reported results are means ± standard deviation. A mixed-repeated measures analysis of variance (ANOVA) was used to assess if differences in kinetic jump variable asymmetries and hip, knee and ankle joint angles at peak eccentric force existed between groups (ACLR and non-ACLR), jump type (bilateral and unilateral) and timings of testing (pre-match, post-match and 48 hours post-match) with a significance set at p<0.05. The magnitude of difference between groups for each jump variable was analysed using Cohen’s d effect sizes. These values have been interpreted in line with a previous study where a small effect size is defined as (<0.2 - 0.6), moderate (0.6-1.2), large (1.2-2) and very large (2-4)33. A one way ANOVA was used to assess differences in GPS variables and RPE between ACL-R and Non-injured groups.

**Results**

During match play there was a significant difference (p= 0.004) between GPS variable total distance covered between the population groups. The distance covered by the non-injured group was 6260.1 ± 524.2m and for the ACL-R group 4919.6 ± 771.7m. For all other GPS variables no significant difference was shown. GPS data reports ‘total time’ of 82.9 ± 0.6 minutes and 71.9 ± 13.5 minutes, ‘high speed running’ of 455.5 ± 141.9m above 5m/s and 300.5 ± 133.5m above 5m/s, meters per minute of 75.5 ± 6.0m/min and 69.0 ± 5.4m/min for non-injured and ACL-R groups respectively. RPE for the non-injured group was 8.6 ± 0.7 and the ACL-R group was 8.1 ± 0.8.

 Asymmetry values are presented in table 3 for the bilateral CMJ and table 4 for the unilateral CMJ. The results from this study show that no significant differences (p<0.05) were found between theACL-R and Non-injured groups, time periods and jump types for all CMJ phase specific variables. Although no significant differences in asymmetries were found, six CMJ variables (out of the 8 CMJ variables analysed) demonstrated a moderate effect size (d=0.6-1.2) between groups across different time points and jump types. These values are shown in tables 3 and 4.

\*\*\*\*\*\*Insert Table 3 here\*\*\*\*\*

\*\*\*\*\*\*Insert Table 4 here\*\*\*\*\*\*

Individual Asymmetry’s for the CMJ variables with the largest effect sizes (>0.90) have been included in (Figures 2 and 3). These were bilateral eccentric rate of force development post 30 minutes (p=0.07, *F*=3.99) and concentric impulse post 48 hours (p=0.07, *F=*3.99).  Subjects 1-7 represent the ACL-R group and 8-14 representing the non-injured group. A positive number indicates asymmetry dominance of the ACL-R leg in the ACL-R group and the right leg of the non-injured group.

\*\*\*\*\*\*Insert Figure 2 here\*\*\*\*\*\*

\*\*\*\*\*\*Insert Figure 3 here\*\*\*\*\*\*

Kinematic data of ankle, knee and hip flexion angles (mean and standard deviation) is presented in table 5. There was a significant time effect difference (F (1,12)=0.36, p=0.038) for average ankle angles in both the bilateral and unilateral CMJ between the time periods of pre to post 30 and post 30 to post 48 (F (1,12)=0.36, p=0.011). However the effect of group x time was not significant (p=>0.05). Knee angles displayed significant differences at pre to post 30 (F (1,12)=0.16, p=0.0001), post 30 to post 48 (F (1,12)=0.16, p=0.049) and post 48 to pre (F (1,12)=0.16, p=0.0001). Finally hip angles displayed significant differences at pre to post 30 (F (1,12)=0.27, p=0.0001) and pre to post 48 (F (1,12)=0.27, p=0.0001). No interaction occurred between groups and jump types.

 \*\*\*\*\*\*Insert Table 5 here\*\*\*\*\*\*

**Discussion**

The aim of this study was to investigate if asymmetries in neuromuscular variables exist between ACL-R and non-injured rugby union athletes during the CMJ. Furthermore, this study investigated whether match fatigue impacted these neuromuscular variables and led to a change in asymmetry values 30 minutes and 48 hours post-match. This is the first study to investigate differences in CMJ phase specific asymmetries between ACL-R and non-injured rugby union players and the effect fatigue has on these asymmetries. Since athletes presenting with asymmetries of >10% are at elevated risk of re-injury, this investigation provides compelling rationale and information for the development of effective RTP processes for rugby players post ACL-R3,14. This study highlights that an individualised analysis of phase specific bilateral and unilateral CMJ variables is likely to produce a robust screening method for RTP criteria, allowing for different positional and physiological demands.

Rugby union players are normally expected back to training 48 hours post-match play. Fatigue enhanced asymmetries present at this time point could lead to unnecessary increased risk of injury for the athlete, however in the current study no mean asymmetry values were over this 10% value from either group. Actions involving a succession of eccentric and concentric muscle actions such as running, cutting, tackling and jumping are crucial components within the sport. The necessity to be able to identify CMJ phase specific asymmetry deficits can inform coaches and medical practitioners with diagnostic information on individual’s neuromuscular status due to the differing nature of eccentric and concentric muscular actions34. This information can then be used to guide further rehabilitation or in adapting training to suit the demands of the individual. Consequently, the aim of this study was to see if significant differences existed in phase specific CMJ asymmetries between ACL-R and non-injured groups between different time points.

This study highlighted no significant interactions between independent variables, timing of testing and jump type even though previous research stated increased sensitivity in identifying asymmetries for vertical jump tasks35. Six of the eight CMJ variables showed moderate effect sizes (d>0.6) at different time points between different jumps. Three of the four CMJ variables that had the highest effect size were within the concentric phase of the CMJ and demonstrated differences between the two groups post-game. Concentric phase changes were also demonstrated by Jordan et al8 whereby significant differences in impulse asymmetries within the elite ski population between ACL-R and uninjured existed in the concentric phase of the jump. Deficits in concentric phase variables have been attributed to knee extensor strength and power deficits, which have been associated with ACL-R27 and linked with changes in vertical jump performance36. In the present study the four CMJ variables that showed the largest effect sizes between groups occurred at testing periods 30 minutes and 48 hours post-match. Nicol et al37 found a bi-modal nature of recovery for CMJ variables to occur post SSC activities immediately,24 and 48 hours post where there was a secondary change occurring at the 48 hour period. Although no 24 hour measures was taken in this study, the bi-modal changes at 48 hour could relate to the larger effect sizes that were seen at that time period. Gathercole et al18 investigated alternative jump measures to quantify neuromuscular fatigue. Most of the CMJ variables were reduced immediately post fatigue and 10 of the measured variables still displayed changes at 72 hours18. However, this study was conducted in college level athletes and only absolute measures were giving rather than asymmetries. It is difficult to ascertain within the present study whether diminished function for absolute values occurred due to the focus on asymmetries. Quantification of absolute function would require further analysis.

Directionality of individual asymmetries presented in figures 2 and 3 indicate that limb dominance for variables, eccentric rate of force development, concentric duration, concentric impulse and concentric mean force were varied in nature. No similarities existed between subjects to demonstrate if deficits in both ACL-R and non-injured groups occurred in the same limb. Previous studies have suggested that acceptable functional deficits in mean limb asymmetries should be <10% in order for potential injury risk to be reduced to an acceptable level38. In this study, all of the mean asymmetries were <10%. The largest individual player asymmetry value presented was -18.1% from the ACL-R group for EccRFD in the unilateral jump 30 minutes post-game. Although no fatigue protocol was used for other studies to formulate an accurate comparison, values are lower than other asymmetry studies where values were found to be up to 20.5% for eccentric impulse in elite male skiers8 but larger than 12.5% found in elite female footballers in single leg CMJ height39. The negative number within this study implies a decreased value in the ACL-R limb. This was an individual case and did not reflect the mean value (-4.6±7.9%) of the ACL-R group. Baumgart et al40 highlighted significant differences in relative force and impulse characteristics in a sedentary population of male and females who had undergone ACL-R. Trends reported in this study differed from those reported in previous literature. Interestingly, some individual cases reported positive asymmetries, representing dominance of the ACL-R limb, rather than healthy limb dominance. This highlights the necessity for including directionality when evaluating asymmetries and the need to investigate further individual participant variation within multi joint actions such as jumping tasks8.

The goal of medical & rehabilitation practitioners working with ACL-R athletes is to regain limb symmetry by restoring function in the injured limb38. The population within this study all participated in regular strength and conditioning programmes that have been tailored towards developing fundamental physical qualities for a successful return to play. The lack of significance within variables could potentially reflect the effective work of the rehabilitation team and strength and conditioning coaches to minimise neuromuscular deficits especially under a fatigued state. Participants were recruited from a variety of teams, all performing different strength and conditioning programmes, a potential reason for the variation in results across both groups. Other studies have utilised populations from the same squad whereby no variation existed between strength and conditioning programming, a potential reason for more conclusive results8,41. Making a comparison between previous research and the current study proves difficult as participants in other studies were mixed in gender; either non-elite collegiate athletes or sedentary and less well trained then the population tested within this study. There is no uniform method for assessing asymmetries and different methods have been used to quantify asymmetry values in each of these previously mentioned studies, leading to inconsistency in findings37. These differences highlight the need for more consistent RTP protocols and standardised reporting of key metrics, enabling data pooling and an increased understanding of the problem.

In this study, significant kinematic changes occurred as a result of fatigue in the ankle, knee and hip between testing times for both groups, although no interaction within group or jump type existed. Holsgaard-Larsen et al7 studied 47 recreational men (23 ACL-R and 25 non-injured) and found a significant reduction in range of motion (ROM) in the ACL-R participants. When comparisons of ROM at the knee joint were performed in the ACL-R group between the operated leg to the non-operated leg at the deepest body centre of mass, deficits in knee flexion angles were present (p<0.001) in unilateral CMJ tasks.  Changes in joint kinematics and adoption of varied coordination patterns have been shown to occur post fatiguing protocol41,42. This is in agreement with findings within the present study, suggesting that fatigue was present within individuals with altered kinematics. Altered movement strategies have also been displayed 48 hours post fatigue protocol whereby a group of rugby union players utilised an increase in eccentric duration to achieve the required impulse for maintenance of CMJ height43. In the present study no significant changes to duration or impulse occurred within kinetic data, kinematic changes show that participants perhaps altered jump strategy as a self-organising mechanism in order to achieve a given movement and maximum output in each CMJ44. Bishop et al proposed that familiarity within a movement task could potentially lead to a decreased inter limb asymmetry value45. Inclusion criteria included familiarity of CMJ within training programmes, which may account for the lack of significant findings. However, this has not been investigated and needs further research to validate this theory.

Several limitations exist within this study. Many of the covariates within the sport of rugby union could play a potential role in confounding the analysis and thus may account for why no significant differences were found in asymmetrical values. Total game time differed between groups with participants in the ACL-R group playing on average 71.86 minutes compared to an average of 82.86 minutes in the non-injured group. This could have had an overall effect on the fatigue that participants were exposed to. Players could not be matched by position due the strict inclusion criteria and the limited number of ACL-R players competing at an appropriate level that satisfy the inclusion criteria. Consequently, variables such as total distance may differ greatly. Only male participants were included within this study due to anatomical variations between sexes. This makes it difficult to apply findings to a female rugby population and is another limitation within this study. Whilst the applied nature of this research adds ecological validity, it is difficult to control the many variables within match play such as total distance covered, number of contacts and high-speed meters run. This may have influenced the level of fatigue induced between groups and therefore affected the CMJ neuromuscular outputs presented by the participants. In order to develop optimal injury prevention strategies for athletes, applied research needs to be specific to the population of interest. With this comes inherent difficulties in accessing professional athletes, so for this reason sample size was relatively small, though this study did meet the subject size required from the sample size calculation (n=6 participants in each group).

Perspective

This study questions the importance of individualising asymmetries as a measure for athletes in complex sports for RTP. Natural variation in participants’ response to loading and fatigue will occur due to differences in previous exposure to stressors. This highlights the necessity for individualised neuromuscular assessment to optimise the rehab process46. Natural asymmetries are likely to exist in athletes within the sport of rugby union due to the variability of training and match play demands. Much research has investigated improvements in absolute force expression capabilities during the CMJ and its positive impact on injury reduction. However, this study highlights that individualised assessment of phase specific asymmetries during a CMJ. This, alongside absolute values mayprovide valuable insight into the RTP process. Further research should focus on investigating these trends across gender types and the longitudinal effects on the risk of injury.  Athletes expressing larger absolute variables may be more resilience to injury even if asymmetry values are greater than the 10% value commonly stated, however this is currently conjecture. A multifactorial model assessing the relationship between both absolute strength and limb symmetry with injury risk would aid practitioners in the production of more focussed screening and strength and conditioning programmes.

References

1.      DallalanaRJ, Brooks JH, Kemp SP. The epidemiology of knee injuries in English professional rugby union. American Journal of Sports Medicine 2007;35:818–30. doi:[10.1177/0363546506296738](https://doi.org/10.1177/0363546506296738).

2.      Kyritsis P, Bahr R, Landreau P, Miladi R, Witvrouw E. Likelihood of ACL graft rupture: not meeting six clinical discharge criteria before return to sport is associated with a four times greater risk of rupture. British Journal of Sports Medicine. 2016;50(15):946–51. doi: 10.1136/bjsports-2016-096410.

3.      Paterno MV, Rauh MJ, Schmitt LC, Ford KR, Hewett TE. Incidence of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary ACL reconstruction and return to sport. Clinical Journal of Sport Medicine. 2012;22:116-121.

4.      Dingenene B, Gokeler A. Optimization of the Return-to-Sport paradigm After Anterior Cruciate Ligament reconstruction: A Critical Step Back to Move Forward. Sports medicine. 2017;47:1487-1500.

5.      KrishnanC, Williams GN. Factors explaining chronic knee extensor strength deficits after ACL reconstruction. Journal of Orthopaedic Research. 2011;29(5):633–640.

6.      Holsgaard-Larsen A, Jensen C, Mortensen NHM, Aagaard P. Concurrent assessments of lower limb loading patterns, mechanical muscle strength and functional performance in ACL-patients: a cross-sectional study. Knee. 2014;10(1):66–73.

7.      Gathercole RJ, Sporer BC, Stellingwerff T, Sleivert GD. Alternative Countermovement-Jump Analysis to Quantify Acute Neuromuscular Fatigue. International Journal of Sports Physiology and Performance. 2014;10:84-92.

8.      Read R, Oliver J, De Ste Croix M, Myer G, Lloyd R. A review of field-based assessments of neuromuscular control and their utility in male youth soccer players. Journal of Strength Conditioning Research. 2018. DOI: 10.1519/0000000000002069

9.      Bishop C, Turner A,  Jarvis P,  Chavda S, Read P. Considerations for Selecting Field-Based Strength and Power Fitness Tests to Measure Asymmetries. Journal of Strength and Conditioning Research. 2017;31(9):2635-2644. doi: 10.1519/JSC.0000000000002023.

10.  Katayama M, Higuchi H, Kimura M. Proprioception and performance after anterior cruciate ligament rupture. International Orthopedics. 2014;28(5):278–281.

11.  King, E, Richter C, Franklyn‐Miller A, Daniels K, Wadey R, Moran R, Strike S. Whole body biomechanical differences between limbs exist 9 months after ACL reconstruction across jump/landing tasks. Scandinavian Journal of Medicine & Science in Sports. 2018;1-12.

12.  Impellizzeri FM, Rampinini E, Maffiuletti N. Marcora SM. A vertical jump force test for assessing bilateral strength asymmetry in athletes. Medicine in Science in Sports and Exercise. 2007;39:2044-2050.

13.  Bell DR, Sanfilippo JL, Binkley N, Heiderscheit BC. Lean mass asymmetry 22 influences force and power asymmetry during jumping in collegiate athletes. Journal of Strength Conditioning Research. 2014;28:884-891.

14.  Grindem H, Logerstedt D, Eitzen I, Moksnes H, Axe MJ, SnyderMackler L. Risberg M. Single-legged hop tests as predictors of self-reported knee function in nonoperatively treated individuals with anterior cruciate ligament injury. American Journal of Sports Medicine. 2011;39:2347–2354. doi:10.1177/0363546511417085.

15.  Montgomery C, Blackburn J, Withers D, Tierney G, Moran C, Simms C. Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases. British Journal of Sports Medicine. 2016;0:1-8. doi: 10.1136/bjsports-2016-096425

16.  Roos PE, Button K, van Deursen RW. Motor Control Strategies during double leg squat following anterior cruciate ligament rupture and reconstruction: an observational study. Journal of Neuroeng Rehabilitation. 2014;11:1-19.

17.  Newton RU, Gerber A, Nimphius S, Shim JK, Doan BK, Robertson M, Pearson DR, Craig BW, Hakkinen K, Kraemer WJ. Determination of functional strength imbalance of the lower extremitites. Journal of Strength and Conditioning Research. 2006;20(4): 971-977.

18.  Jordan MJ, Aagaard P, Herzog W. Lower limb asymmetry in mechanical muscle function: A comparison between ski racers with and without ACL reconstruction. Scandanavian Journal of Medicine and Science in Sports. 2015;25:301-309.

19.  Chavda S, Bromley T, Jarvis P, Bishop C. Force-time Characteristics of the Countermovement Jump: Analysing the Curve in Excell. Strength and Conditioning Journal. 2017;40:67-77.

20.  Gathercole RJ, Sporer BC, Stellingwerff T. Countermovement Jump Performance with Increased Training Loads in Elite female Rugby Athletes. International Journal of Sports Medicine. 2015;36(9):722-728.

21.  Jakobsen MD, Sundstrup E, Randers MB, Kjær M, Andersen L, Krustrup P. The effect of strength training, recreational soccer and running exercise on stretch-shortening cycle muscle performance during countermovement jumping. Human Movement Science. 2012;31(4):970–986.

22.  Duncan A, McDonagh MJ. Stretch reflex distinguished from pre-programmed musclenactivations following landing impacts in man. Journal of Physiology. 2000.15;526(2):457-68.

23.  Johnston RB, Howard ME, Cawley PW, Losse GM. Effect of lower extremity muscular fatigue on motor control performance. Medicine and Science in Sports and Exercise. 1998;30(12):1703-1707.

24.  Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. Journal of Orthopedics in Sports Physical Therapy. 2006;36(6):385-402.

25.  Brophy RH, Schmitz L, Wright RW, Dunn WR, Parker RD, Andrish JT, McCarty EC, Spindler KP. Return to Play and Future ACL Injury Risk After ACL Reconstruction in Soccer Athletes From the Multicenter Orthopaedic Outcomes Network (MOON) Group. The American Journal of Sports Medicine. 2012;40(11): 517-22. doi: 10.1177/0363546512459476.

26.  Roe G, Darrall-Jones J, Till K, Phibbs P, Read D, Weakley J, Jones B. To Jump or Cycle? Monitoring Neuromuscular Function in Rugby Union Players. International Journal of Sports Physiology and Performance. 2017;12:690-696.

27.  Granan L, Inacio M. Sport-specific injury pattern recorded during anterior cruciate ligament reconstruction. American Journal of Sports Medicine. 2013;41(12):2814–2818.

28.  Menzel HJ, Szmuchrowski LA, Araujo S, Andrade, AGP. Analysis of Lower Limb Asymmetries by Isokinetic and Vertical Jump Tests in Soccer Players. Journal of strength and conditioning research. 2013;27(5):1370-1377.

29.  McMahon JJ, Murphy S, Rej S, Comfort P. Countermovement Jump Phase Characteristics of Senior and Academy Rugby League Players. International Journal of SportsPhysiology and Performance. 2016;12(6):803-811. doi: 10.1123/ijspp.2016-0467.

30.  Owen NJ, Watkins J, Kilduff LP, Bevan HR, Bennett MA. Development of a Criterion Method to Determine Peak Mechanical Power Output in a Countermovement Jump. Journal of Strength Conditioning Research. 2014;28(6):1552-1558.

31.  Cunningham D, Shearer DA, Drawer S, Eager R, Taylor N, Cook C, Kilduff LP. Movement Demands of Elite U20 International Rugby Union Players. PLoS One. 11(4). doi:10.1371/ journal.pone.0153275

32.  Borg G. Borg's perceived exertion and pain scales. Champaign, IL, US: Human Kinetics; 1998.

33.  Yanci J, Camara J. Bilateral and Unilateral vertical ground reaction force and leg asymmetriesin soccer players. Biology of Sport. 2016;33(2):179-183. doi:10, 5604/20831862.1198638

34.  Aagaard P. Training-induced changes in neural function. Exercise and Sport Science reviews. 2003;31(2):61-67.

35.  Lockie R, Callagham S, Berry S, Cooke E, Jordan C, Luczo T, Jeffries M. Relationship between unilateral jumping ability and asymmetry on multidirectional speed in team-sport athletes. Journal of Strength and Conditioning Research. 2014;28:3557-3566.

36.  Fischer F, Blank C, Dunnwald T, Gfoller P, Herbst E, Hoser C Fink C. Isokinetic Extension Strength is Associated with Single-Leg Vertical Jump Height. The Orthopaedic Journal of Sports medicine. 2017;5(11). doi: 10.1177/2325967117736766.

37.  Nicol C, Avela J, Komi PV. The stretch-shortening cycle: a model to study naturally occurring neuromuscular fatigue. Sports Medicine. 2006;36:977-999.

38.  Bishop C, Turner A, Read P. Effects of inter-limb asymmetries on physical and sports performance: a systematic review. Journal of Sports Sciences. 2017;36(10).

39.  BaumgartC, Hoppe MW, Freiwald J. Phase-Specific Ground Reaction Force Analyses of Bilateral and Unilateral Jumps in Patients With ACL Reconstruction. Orthopaedic Journal of Sports Medicine. 2017;5(6).doi: 10.1177/2325967117710912

40.  Cowley JC, Gates DH. Proximal and distal muscle fatigue differentially affect movement coordination. PLoS ONE. 2017;12(2). doi:10.1371/journal.pone.0172835

41.  Zebis M, Bencke J, Andersen L. Acute fatigue impairs neuromuscular activity of anterior cruciate ligament-agonist muscles in female team handball players. Scandinavian Journal of Medicine & Science in Sports. 2010;21(6):833-840.

42.  Kennedy RA, Drake D. The effect of acute fatigue on countermovement jump performance in rugby union players during preseason. The Journal of Sports Medicine and Physical Fitness. 2017;57(10):1261-1266.

43.  Hamill J, Van Emmerik RE, Heiderscheit BC, Li L. A dynamical systems approach to lower extremity running injuries. Clinical biomechanics. 1999;14:297–308.

44.  Bishop C, Read P, Mccubbine J, Turner AN. Vertical and Horizontal Asymmetries are Related to Slower Sprinting and Jump Performance in Elite Youth Female Soccer Players. The Journal of Strength and Conditioning. 2018; [Epub ahead of print].  doi: 10.1519/JSC.0000000000002544.

45.  Impellizzeri FM, Rampinini E, Marcora SM. Physiological assessment of aerobic training in soccer. Journal of Sports Science. 2005;23:583–592. doi: 10.1080/ 02640410400021278

Tables

*Table 1. Participant descriptive statistics.*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Participant | **Days between Surgery and Assessment (including ACL-R knee)** | **Position** | **Height (cm)** | **Weight (kg)** | **Age** |
| 1 | 437 (R) | Centre | 186 | 105 | 23 |
| 2 | 504 (L) | Fullback | 185 | 104 | 27 |
| 3 | 618 (L) | Winger | 180 | 93 | 26 |
| 4 | 335 (R) | Centre | 191 | 99.6 | 20 |
| 5 | 313 (L) | Second Row | 194 | 102 | 25 |
| 6 | 546 (L) | Prop | 184 | 114 | 20 |
| 7 | 455 (L) | Hooker | 183 | 113.2 | 23 |
|  | **Average** |  | **186** | **104** | **23** |
|  | **Standard Deviation** |  | **4** | **7** | **3** |
| 8 | Non-injured | Winger | 181 | 99 | 31 |
| 9 | Non-injured | Back Row | 183 | 100 | 24 |
| 10 | Non-injured | Second Row | 198 | 104 | 21 |
| 11 | Non-injured | Scrum Half | 178 | 83 | 23 |
| 12 | Non-injured | Winger | 179 | 89 | 26 |
| 13 | Non-injured | Back Row | 187 | 99 | 26 |
| 14 | Non-injured | Fly Half | 179 | 94 | 30 |
|  | **Average** |  | **184** | **95** | **26** |
|   | **Standard Deviation** |  | **7** | **7** | **3** |

*Table 2*. Description of Countermovement Jump variables

|  |  |
| --- | --- |
| **Jump Variable** | **Description** |
| Mean Concentric Force (N) (MeanConForce) | Mean force generated during the concentric phase |
| Mean Eccentric force (N) (MeanEccForce) | Mean force generated during the eccentric phase |
| Concentric Impulse (N.s) (ConImp) | Net force exerted concentrically multiplied by the time taken concentrically |
| Eccentric Impulse (N.s) (EccImp) | Net force exerted eccentrically multiplied by the time taken concentrically |
| Concentric Duration (s) (ConDur)                       | Length of time required to perform the concentric CMJ phase |
| Eccentric Duration (s) (EccDur) | Length of time required to perform the eccentric CMJ phase |
| Concentric Rate of Force Development (N.s¯¹) (ConRFD) | Largest force produced in the concentric phase divided by the concentric duration |
| Eccentric Rate of Force Development (N.s¯¹) (EccRFD) | Largest force produced in the eccentric phase divided by the eccentric duration |

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Pre** |  |  |  | **Post 30** |  |  |  | **Post 48** |  |  |
| **Jump Variables** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** |
| Eccentric Mean Force | 0.7 (5.8) | 1.9 (8.2) | 0.76 | 0.17 | -1.2 (7.0) | 1.9 (7.4) | 0.44 | 0.43 | -1.4 (8.0) | 1.0 (6.4) | 0.55 | 0.33 |
| Concentric Mean Force | -0.1 (4.4) | 2.1 (2.4) | 0.25 | 0.64 | -1.6 (5.4) | 2.2 (3.2) | 0.13 | 0.86 | -2.4 (6.1) | 1.6 (4.0) | 0.18 | 0.77 |
| Eccentric Impulse | -1.8 (10.4) | 4.2 (12.4) | 0.34 | 0.53 | 2.4 (12.8) | -1.7 (9.0) | 0.50 | 0.37 | -1.7 (17.7) | 0.6 (6.3) | 0.75 | 0.17 |
| Concentric Impulse | -2.4 (8.2) | -0.2 (5.9) | 0.56 | 0.32 | -1.9 (8.4) | 0.5 (8.4) | 0.61 | 0.28 | -7.0 (9.4) | 1.8 (6.9) | 0.07 | 1.07 |
| Eccentric Duration | -3.9 (13.5) | 5.3 (8.2) | 0.15 | 0.82 | 3.7 (7.9) | -1.4 (3.3) | 0.14 | 0.85 | -0.5 (7.4) | 0.9 (7.3) | 0.73 | 0.19 |
| Concentric Duration | 0.1 (6.2) | 1.3 (7.7) | 0.75 | 0.17 | -0.9 (6.3) | 4.5 (4.9) | 0.1 | 0.94 | 0.9 (6.5) | 3.1 (6.1) | 0.5 | 0.36 |
| Eccentric Rate of Force Development | 3.9 (17.8) | -1.6 (9.2) | 0.48 | 0.39 | -4.6 (7.9) | 3.7 (7.6) | 0.07 | 1.07 | 3.8 (9.6) | -1.3 (11.5) | 0.31 | 0.48 |
| Concentric Rate of Force Development | -0.6 (5.0) | 1.2 (8.6) | 0.65 | 0.25 | -1.8 (5.7) | -2.4 (4.6) | 0.83 | 0.12 | -3.7 (9.4) | -1.7 (4.6) | 0.63 | 0.26 |

*Table 3*. Bilateral CMJ percentage asymmetry (mean (±SD)) between the ACL-R and non-injured participant groups.

Note: A positive number represents ACL-R leg dominance in the ACL-R groups and right leg dominance in the non-injured group.\*represents a significant difference between groups. d=Cohens Effect size between groups. #represents a significant difference between time points pre and post 30. § represents a significant difference between time points pre and post 48. ¥ represents a significant difference between time points post 30 and post 48.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  |  | **Pre** |  |  |  | **Post 30** |  |  |  | **Post 48** |  |  |
| **Jump Variables** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** | **ACL-R** | **Non-injured** | **P Value** | **Effect Size (d)** |
| Eccentric Mean Force | 1.4 (3.9) | 0.1 (3.2) | 0.52 | 0.36 | -0.5 (3.8) | 2.5 (6.8) | 0.33 | 0.54 | 1.8 (4.0) | -1.6 (3.8) | 0.13 | 0.88 |
| Concentric Mean Force | 0.7 (6.5) | -1.0 (3.0) | 0.55 | 0.33 | 0.4 (1.8) | 0.2 (2.4) | 0.89 | 0.07 | 0.9 (3.0) | -0.4 (3.3) | 0.45 | 0.93 |
| Eccentric Impulse | 1.6 (8.8) | 1.2 (7.5) | 0.92 | 0.05 | -1.6 (10.6) | 4.1 (11.8) | 0.37 | 0.50 | 3.0 (8.1) | -3.4 (7.1) | 0.14 | 0.85 |
| Concentric Impulse | 2.8 (6.6) | -1.7 (6.5) | 0.21 | 0.71 | 3.7 (9.8) | -4.4 (8.6) | 0.13 | 0.88 | 4.4 (9.7) | -0.2 (8.6) | 0.37 | 0.49 |
| Eccentric Duration | -2.4 (6.0) | 0.8 (5.3) | 0.31 | 0.57 | -1.0 (4.7) | 1.2 (10.6) | 0.62 | 0.27 | -3.3 (9.1) | 1.7 (8.4) | 0.31 | 0.57 |
| Concentric Duration | 4.8 (8.1) | 1.1 (5.2) | 0.33 | 0.54 | 2.2 (7.5) | -4.9 (11.2) | 0.19 | 0.74 | 0.5 (4.0) | 0.9 (5.6) | 0.88 | 0.08 |
| Eccentric Rate of Force Development | 2.1 (9.0) | 0.1 (8.0) | 0.67 | 0.23 | 7.5 (21.3) | -0.3 (13.5) | 0.43 | 0.44 | 3.8 (9.6) | -1.3 (11.5) | 0.39 | 0.48 |
| Concentric Rate of Force Development | -3.9 (8.3) | -1.7 (7.3) | 0.61 | 0.28 | -2.9 (8.0) | 0.5 (4.1) | 0.33 | 0.54 | -0.3 (5.2) | -1.8 (7.4) | 0.66 | 0.24 |

*Table 4*. Unilateral CMJ percentage asymmetry (mean (±SD)) between the ACL-R and non-injured participant groups.

Note: A positive number represents ACL-R leg dominance in the ACL-R groups and right leg dominance in the non-injured group.\*represents a significant difference between groups. d=Cohens Effect size between groups. #represents a significant difference between time points pre and post 30. § represents a significant difference between time points pre and post 48. ¥ represents a significant difference between time points post 30 and post 48.

|  |  |  |  |
| --- | --- | --- | --- |
|   | **Bilateral** | **Unilateral Right** | **Unilateral Left** |
|   | **ACL-R** | **Healthy** | **ACL-R** | **Healthy** | **ACL-R** | **Healthy** |
| Ankle |  |
| Pre | 88.8 (5.3) | 88.26 (4.5) | 88.7 (3.3) | 87.7 (5.7) | 90.5 (4.5) | 89.4 (2.8) |
| Post 30 mins | 89.4 (2.7) | 87.52 (5.1) | 88.1 (3.1) | 86.2 (5.1) | 89.6 (4.0) | 91.7 (3.7) |
| Post 48 hrs | 92.0 (1.2) | 88.8 (5.4) | 89.0 (3.3) | 87.0 (4.8) | 90.4 (2.4) | 91.1 (3.3) |
| Knee |   |
| Pre | 103.4 (10.3) | 99.0 (10.3) | 114.6 (5.5) | 114.8 (8.1) | 111.1 (5.2) | 112.1 (7.7) |
| Post 30 mins | 102.7 (10.3) | 103.0 (9.0) | 115.9 (8.1) | 115.7 (9.5) | 111.5 (9.1) | 115.5 (6.8) |
| Post 48 hrs | 102.9 (8.4) | 98.8 (11.4) | 115.1 (7.9) | 114.3 (7.6) | 105.9 (13.7) | 102.1(9.9) |
| Hip |   |
| Pre | 79.2 (11.2) | 78.0 (13.0) | 103.3 (11.5) | 99.1 (11.2) | 106.0 (10.0) | 97.8 (10.8) |
| Post 30 mins | 81.7 (14.9) | 80.5 (17.6) | 105.8 (18.3) | 101.6 (12.4) | 106.3 (18.1) | 101.9 (12.1) |
| Post 48 hrs | 80.1 (15.6) | 77.6 (14.2) | 103.3 (16.7) | 102.2 (8.6) | 105.9 (13.7) | 102.1 (9.9) |

*Table 5.* Ankle, knee and hip angles (mean(±SD)) for bilateral and unilateral right and left CMJ at 3 different time points.

Note: \*represents a significant difference between groups.

Figures

*Figure 1*.Typical force-time (black line) trace with associated velocity-time (red line) trace to distinguish between the three phases of a CMJ.



*Figure 2*. Individual asymmetry percentages for bilateral and unilateral eccentric rate of force development, Post 30 minutes (Positive values are representative of absolute scores being greater on ACL-R leg in ACL-R group or right leg of non-injured group).



*Figure 3*. Individual asymmetry percentages for bilateral and unilateral concentric impulse, Post 48 hours (Positive values are representative of absolute scores being greater on ACL-R leg in ACL-R group or right leg of non-injured group).

 