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Medio-lateral Knee Fluency in Anterior Cruciate Ligament-Injured Athletes During Dynamic Movement Trials

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Abstract

Background—Correction of neuromuscular impairments after anterior cruciate ligament injury is vital to successful return to sport. Frontal plane knee control during landing is a common measure of lower-extremity neuromuscular control and asymmetries in neuromuscular control of the knee can predispose injured athletes to additional injury and associated morbidities. Therefore, this study investigated the effects of anterior cruciate ligament injury on knee biomechanics during landing.

Methods—Two-dimensional frontal plane video of single leg drop, cross over drop, and drop vertical jump dynamic movement trials was analyzed for twenty injured and reconstructed athletes. The position of the knee joint center was tracked in ImageJ software for 500 milliseconds after landing to calculate medio-lateral knee motion velocities and determine normal fluency, the number of times per second knee velocity changed direction. The inverse of this calculation, analytical fluency, was used to associate larger numerical values with fluent movement.

Findings—Analytical fluency was decreased in involved limbs for single leg drop trials ($P=0.0018$). Importantly, analytical fluency for single leg drop differed compared to cross over drop trials for involved ($P<0.001$), but not uninvolved limbs ($P=0.5029$). For involved limbs, analytical fluency values exhibited a stepwise trend in relative magnitudes.

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Conflicts of Interest: None

Interpretation—Decreased analytical fluency in involved limbs is consistent with previous studies. Fluency asymmetries observed during single leg drop tasks may be indicative of abhorrent landing strategies in the involved limb. Analytical fluency differences in unilateral tasks for injured limbs may represent neuromuscular impairment as a result of injury.

Keywords

Anterior cruciate ligament (ACL) injury; ACL injury prevention; frontal plane knee biomechanics; knee fluency; dynamic landing knee kinematics

1. INTRODUCTION

Each year, approximately 250,000 athletes undergo anterior cruciate ligament (ACL) reconstruction (ACLR) surgery following ligament rupture with the intent to return these athletes to pre-injury levels of activity (19). In addition to physical damage, the traumatic nature of ACL rupture may contribute to psychological distress in athletes after injury (40). While knee function alone can delay the return to previous levels of activity (38, 39), successful rehabilitation is highly dependent on pain and psychological perceptions (41). Importantly, the mechano-receptors encapsulated in the ACL likely do not re-innervate the graft and pre-injury levels of sensation, kinesthesia, and proprioception likely do not return to the knee joint (43, 44). Individuals that lack confidence in the injured limb may not fully benefit from surgical or therapeutic procedures (37).

Although ACLR and the subsequent rehabilitation return stability to knee joint, substantial functional asymmetries may persist in athletes clinically cleared to return to competition (17, 18). Such biomechanical asymmetries in strength and function are predictive of primary ACL injury in healthy athletes (21, 22, 23, 24, 25, 26) and augment the significant risk to suffer a second ACL injury (20). Asymmetric performance may also be a harbinger of deficits in neuromuscular control, associated with both primary (3, 27, 28, 29) and secondary ACL injury (25, 30). Accordingly, quantifiable parameters of frontal plane knee biomechanics during landing, associated with neuromuscular control, are frequently assessed in high ACL injury risk individuals and ACL-injured patients (1).

Three-dimensional (3D) motion analysis effectively and reliably measure lower limb positioning during clinical dynamic movement trials (9, 10, 11, 12). However, the cost and spatial requirements generally make these technologies unavailable in a clinical setting. A validated two-dimensional (2D) frontal plane approach that uses a standard video camera to measure knee biomechanics may provide clinicians a cost-effective alternative to 3D motion capture (10, 13, 14). McLean et al. (2005) validated 2D motion analysis of dynamic movement trials, in which the knee joint center is readily recognized, to characterize frontal plane knee motion (15). The reliability of 2D video analyses for the measurement of frontal plane knee valgus during the DVJ and single leg dynamic movement tests was further demonstrated by Munro et al. (2012).

Knee fluency is a recently introduced measure that incorporates time-dependent assessments of medio-lateral knee displacement and neuromuscular control during the landing portion of dynamic movement tasks (1). Fluency varies between healthy, ACLR, and conservatively

treated subjects. Decreased fluency is indicative of incomplete reestablishment of healthy landing strategies for ACL-injured individuals (1). Therefore, rehabilitation and neuromuscular training programs designed to prevent injury or restore limb function may target fluency as a quantifiable parameter to assess the progression of frontal plane knee mechanics.

A variety of clinical tests may be used to evaluate biomechanical movement patterns that have the ability to supplement ACL injury risk among athletes (2, 3, 4). Greater knee abduction moment during bilateral landing tasks, such as the drop vertical jump (DVJ), is indicative of ACL injury risk with high sensitivity and precision in female athletes (3). Furthermore, increased attention has been devoted to unilateral clinical tests, such as the single leg drop (SLD) and the crossover drop (COD) as a result of evidence that implicates single leg landings and directional changes as the most frequent contributors to ACL injury (6, 7, 8).

Based upon these prior investigations, we sought to determine the effects of ACL injury on bilateral knee biomechanics during SLD, COD, and DVJ dynamic movement trials between injured and uninjured limbs using 2D frontal plane video analyses. We hypothesized that: (1) Knee fluency would be decreased for involved limbs and would be accompanied by increased medial knee displacement for SLD and COD trials, but not for DVJ tests and (2) Knee fluency would follow the general trend: COD < SLD < DVJ for both involved and uninvolved limbs.

2. METHODS

Twenty ACL-injured athletes (n=20; Males n=10, Age: mean 19.8 years (SD 4.7 years), Height: mean 178.5 cm (SD 6.4 cm), Weight: mean 85.8 kg (SD 14.3 kg); Females n=10, Age: mean 19.8 years (SD 13.2 years), Height: mean 165.0 cm (SD 4.3 cm), Weight mean 63.5 kg (SD 9.4 kg) participated in a series of DVJ, SLD, and COD dynamic movement tests. All dynamic movement tasks were performed from a 32 cm high stationary platform; all subjects were outfitted with Nike Air Pegasus+ 28 Team sneakers (Nike, Inc., Beaverton, OR). The DVJ is a biphasic-landing task in which an individual drops from a stationary platform, lands on both feet, rebounds to a maximal vertical jump, and recovers with a two foot landing (5). To perform the SLD, an athlete balances on a single leg, drops from a stationary platform, and lands on the same limb. Similarly, to complete a COD, the subject jumps laterally from an elevated platform off one leg and lands on the contralateral limb in a balanced ground position. The lateral motion component of the COD trial was unconstrained. Subjects jumped from the middle of the elevated platform to a ground-level landing zone. The distance from the middle of the elevated platform to the proximal edge of the landing zone was 26.67 cm; the ground-level landing zone was 60.96 cm wide.

Two-dimensional frontal plane videos for 216 SLD trials, 216 COD trials, and 101 bilateral DVJ trials were obtained. All video clips were processed using GoPro Studio software (GoPro Inc., San Mateo, California) to remove fish-eye distortion. ImageJ software (ImageJ, National Institutes of Health, Bethesda, Maryland) was used to determine definitive landing time points and track the position of the knee joint center throughout the landing phase for

each video clip. For each image within a clip stack, positional values based on pixel elements were discretely defined as constituents of a 2D Euclidean space within ImageJ. The z-position of an image within the clip stack was defined in accordance with the frame rate of the GoPro camera. In this manner, the ImageJ video analysis software precisely assessed spatial and temporal knee motion in the 2D frontal plane.

The position of the toe was first identified and defined in multiple images before and after visual estimation of landing. Definitive landing was described as the first image within a clip stack after which no appreciable vertical position change of the toe occurred. The landing phase of a dynamic movement task was defined as 500 milliseconds after definitive landing. Using the GoPro frames per second rate of 59.94, the entirety of the landing phase of the trial was defined using discrete image numbers within a clip stack.

After the identification of the landing image in the stack of images, the knee joint center was identified and tracked throughout the z-position images comprising the landing phase. A vertical line, guided by a retro-reflective marker placed on the skin near the tibial tuberosity, was drawn in ImageJ to intersect with a horizontal line, guided by markers placed on the skin near medial and lateral epicondyles of the knee for each image within the landing phase portion of a clip stack. The intersection of the two lines, defined as the knee joint center, was calculated in MATLAB using the endpoints of the vertical and horizontal lines. Medio-lateral positional values were used to measure knee joint center displacements. The medial displacement of the knee joint center for a dynamic movement trial was defined as the absolute value of the difference between the maximum medial position of the knee and the knee joint center position at landing. The lateral displacement of the knee joint center for a dynamic movement trial was defined as the absolute value of the difference between the maximum lateral position of the knee and the knee joint center position at landing. The medio-lateral range of the knee joint center was defined as the absolute difference between the maximum medial and lateral displacement of the knee during the landing phase of a dynamic movement trial. Knee displacement parameters were compared between involved and uninvolved limbs across SLD, COD, and DVJ dynamic movement trials.

As an integral component of fluency and displacement calculations, 2D frontal plane knee velocities were calculated from medio-lateral positional values and analyzed for involved and uninvolved limbs across SLD, COD, and DVJ trials. The distance per pixel for a given image was determined to be 0.606 centimeters. Using the GoPro frame rate as an indicator of the z-position, time differences between images in a clip stack, and pixel-distance values, the raw medio-lateral knee velocity data were converted to meter per second velocity values. For the purpose of this study, the average medio-lateral velocity of the knee throughout a single dynamic movement trial was determined.

Raw knee velocities were plotted as a function of time to determine fluency. Velocities less than 10% of the absolute maximum for a given trial were filtered from the data set as an artifact of 2D video analysis. A polynomial, generated in MATLAB, was fitted to the velocity versus time graph and used to ascertain all relevant parameters in knee fluency calculations. The real, unique roots of the polynomial were depicted graphically, and visually confirmed to determine fluent events. A fluent event, denoted by a root of the

polynomial, was defined as the point at which the medio-lateral velocity of the knee changed direction in the 2D frontal plane. Knee fluency was calculated as the number of fluent events per unit time and defined as normal fluency or F_N . For statistical analyses, the inverse of F_N was used such that larger values indicated greater fluency; this value was defined as analytical fluency or F_A .

As the quotient of time and the number of fluent events, F_A possesses a natural limit at zero, whereby the number of fluent events approaches infinity. Accordingly, the degree of the polynomial was based on previous F_A data reported by Roos et al. (2014). Mean analytical fluency values for ACL-injured subjects in this study were 0.14 seconds (SD 0.34), corresponding to 7.14 fluent events per second (1). In an effort to capture the majority of the F_A distribution, keeping in mind the natural limit of F_A at zero, the degree of the polynomial was calculated from the F_A values corresponding to 0.25 SD below the reported F_A mean of 0.14 seconds. This F_A value, 0.055 seconds, corresponds 18.18 fluent events per second. As our collection time was limited to 500 milliseconds after landing, 9.09 fluent events would occur in this scenario. As such, the order of the polynomial, corresponding to the upper limit of the amount of observable roots, or fluent events, was chosen to be 9. Recognizing that some roots of the polynomial may be degenerate for a given trial, the real, unique roots were depicted graphically, and visually confirmed to determine fluent events (Figure 1).

2.1. STATISTICAL METHODS

Medio-lateral knee range, F_A , and velocity values were compared between involved and uninvolved limbs using a paired two-sample t -test. One-way Analysis of Variance (ANOVA) testing was used to compare mean F_A values between SLD, COD, and DVJ trials for involved and uninvolved limbs. Post-hoc paired two-sample t -tests were performed to compare F_A relationships for dynamic movement trials grouped by involved and uninvolved limb status. An *a priori* α -value of 0.05 was used to determine statistical significance for all tests. All numerical values are displayed as mean and SD (standard deviation).

3. RESULTS

3.1. MEDIO-LATERAL KNEE DISPLACEMENT

The mean medio-lateral range of the knee joint center movement during SLD trials was 5.30 centimeters (SD 1.96 cm) for involved limbs and 6.03 cm (SD 2.28 cm) for uninvolved limbs ($P=0.0147$). Similarly, the mean knee joint center range of motion for COD trials was 10.22 cm (SD 2.98 cm) for involved limbs and 10.73 cm (SD 3.64 cm) for uninvolved limbs ($P=0.2683$); for DVJ trials, the mean medio-lateral range of the involved limb was 5.64 cm (SD 1.97 cm), while the range of the uninvolved limb was 6.09 cm (SD 2.17 cm) ($P=0.1105$; Figure 2). There was no difference between involved and uninvolved limbs in the maximum medial knee displacement during landing for SLD, 3.02 cm (SD 2.20 cm) and 3.60 cm (SD 2.74 cm) ($P=0.0981$); COD, 10.07 cm (SD 3.18 cm) and 10.44 cm (SD 3.96 cm) ($P=0.4379$), or DVJ trials 2.48 cm (SD 1.96 cm) and 3.02 cm (SD 2.47 cm) ($P=0.0794$; Figure 2).

3.2. KNEE FLUENCY

Mean F_A values for involved and uninvolved limbs were 0.143 seconds (SD 0.062 sec) and 0.189 sec (SD 0.107 sec) for SLD trials, respectively, ($P=0.0018$); 0.208 sec (SD 0.121 sec) and 0.199 sec (SD 0.106 sec) for COD trials, respectively, ($P=0.56$); and 0.244 sec (SD 0.122 sec) and 0.259 sec (SD 0.133 sec) for DVJ trials, respectively, ($P=0.41$; Figure 4).

F_A values for involved and uninvolved limbs differed between SLD, COD, and DVJ trials (involved: $P<0.001$; uninvolved: $P<0.001$). (Figure 5) *Post-hoc t*-tests were conducted between trials for involved and uninvolved F_A data. For the uninvolved limb, knee F_A differed between DVJ versus SLD trials ($P<0.001$) and DVJ versus COD trials ($P=0.004$; Figure 5). Knee F_A values for SLD versus COD trials were not different for the uninvolved limb ($P=0.5029$). Similar relationships in knee F_A between DVJ versus SLD trials ($P<0.001$) and DVJ versus COD trials ($P=0.0319$) were demonstrated for the involved limb. Importantly, the involved limb F_A values differed between SLD and COD trials ($P<0.001$), which established the relationship for the involved limb of: SLD < COD < DVJ. (Figure 5)

3.3. MEDIO-LATERAL KNEE VELOCITY

The mean R-squared value for the polynomial fit to the velocity versus time graphs was 0.44. The average 2D frontal plane knee velocities for involved limbs were 0.34 m/s (SD 0.079 m/s), 0.44 m/s (SD 0.085 m/s), and 0.32 m/s (SD 0.087 m/s) for SLD, COD, and DVJ trials, respectively. Medio-lateral knee velocity averages for uninvolved limbs were 0.34 m/s (SD 0.077 m/s), 0.46 m/s (SD 0.099 m/s), and 0.31 m/s (SD 0.095 m/s) for SLD, COD, and DVJ trials, respectively. Asymmetries in the average medio-lateral velocity of the knee throughout the landing phase were not observed between involved and uninvolved limbs for SLD ($P=0.8369$), COD ($P=0.1562$), or DVJ ($P=0.4081$) dynamic movement tests. (Table 1)

Maximum 2D frontal plane knee velocities for involved limbs were 1.08 m/s (SD 0.271 m/s), 1.73 m/s (SD 0.54 m/s), and 1.06 m/s (SD 0.34 m/s) for SLD, COD, and DVJ trials, respectively. The recorded maximum knee velocities for uninvolved limbs were 1.17 m/s (SD 0.41 m/s), 1.80 m/s (SD 0.51 m/s), and 0.99 m/s (SD 0.22 m/s) for SLD, COD, and DVJ trials, respectively. Maximum 2D frontal plane knee velocities were not significantly different between involved and uninvolved limbs (SLD: $P=0.1651$; COD: $P=0.4574$; DVJ: $P=0.1418$). (Table 1)

4. DISCUSSION

This study measured 2D frontal plane knee mechanics in ACL-injured athletes during the landing phase of multiple dynamic tasks. A stepwise trend in knee F_A was observed for the involved limb between the dynamics tasks, such that SLD < COD < DVJ, which differed from the initially hypothesized trend: COD < SLD < DVJ. The involved limb demonstrated significantly less knee F_A compared to the uninvolved limb during SLD trials. Knee F_A for injured and healthy limbs measured by Roos et al. for single leg hop trials was comparable to the fluency values recorded by our group in SLD trials (Roos et al.: Involved: mean 0.14 sec (SD 0.34 sec), Uninvolved: mean 0.17 sec (SD 0.41 sec), Panos et al.: Involved: mean 0.14 sec (SD 0.062 sec), Uninvolved: mean 0.19 sec (SD 0.11 sec)).

As expected, our results demonstrate that landing phase knee stability quantified by F_A is significantly greater for bilateral compared to unilateral tasks (DVJ vs. SLD or COD) for both involved and uninvolved limbs. Yet, differences in knee F_A between SLD and COD trials were significant for involved limbs, but not uninvolved limbs. These findings may indicate that the involved limb mediates landing and stabilization in a macroscale, movement trial-dependent manner. This contrasts the consistent manner observed between SLD and COD trials of uninvolved limbs. Variability in landing strategies, which results in exposure to adverse biomechanical values for knee F_A for seemingly similar unilateral tasks, may be a direct manifestation of clinical reports of impaired neuromuscular control after ACLR surgery (42). Additionally, knee fluency asymmetries may also help to explain elevated re-injury rates (33) and the advanced development of chronic morbidities (32) observed in injured limbs. This difference in F_A may indicate that the involved limb has developed maladaptive landing techniques or has not completely reestablished healthy landing and stabilization mechanisms in comparison with the uninvolved limb for single leg tasks. Furthermore, while the SLD trial displayed the only significant difference in F_A when compared directly between involved and uninvolved limbs, an expected difference in F_A was not observed in COD trials.

While the knee joint center did not display significant displacement asymmetries in the medial direction between involved and uninvolved limbs for any dynamic movement trial, the effective range of the joint during landing displayed asymmetric tendencies. The holistic evaluation of medio-lateral knee joint range provided a manner in which to control for inherent dynamic movement trial-specific differences that predispose knee displacement in the medial or lateral direction (consider SLD versus COD). Furthermore, the failure to observe significant medial knee excursions in involved limbs, commonly associated with a deficit of neuromuscular control, is notable. Significant asymmetries in the medio-lateral displacement of the knee joint center have been identified previously as adverse landing strategies for the ACL injured individuals (1). The supposition relating medial knee displacement and other limb asymmetries to deficits of neuromuscular control has been well characterized (20, 25, 34, 35, 36).

4.1. LIMITATIONS

Although almost 650 individual data points were obtained from over 500 dynamic movement trials, this study examined a relatively small cohort ($n=20$). Furthermore, toe angulation during landing followed by the natural flexion of the knee could produce knee displacement in the medial or lateral 2D frontal plane as a result of regular landing strategies as opposed to biomechanically-unhealthy movement quantified by diminished fluency or increased medial knee displacement values. Although the effects of toe angulation were not thought to significantly alter the findings of this study, this limitation is indicative of the shortcomings of 2D frontal plane video analyses in capturing multiplanar motions, such as dynamic knee valgus (45). As knee fluency is a uniplanar parameter, 2D frontal plane video was deemed an appropriate analytical method for this study, however further analyses should be performed using 3D motion capture software to corroborate and expand upon the observed results would be beneficial.

5. CONCLUSION

Neuromuscular control of frontal plane knee motion during dynamic movement trials is an important factor to assess during the rehabilitation process of ACL-injured athletes. Medio-lateral knee fluency has been identified as a novel indicator of knee stability during landing. This study is the first to describe differences in medio-lateral knee fluency for ACL-injured and uninjured limbs across SLD, COD, and DVJ dynamic movement trials. The current findings demonstrate significant inter-limb differences in medio-lateral knee control, directly supporting the notion of perturbed neuromuscular control after ACL injury and ACLR surgery. Additionally, this study was performed using 2D frontal plane video, precluding the need for prohibitively spacious or costly 3D motion capture equipment (45, 15). The use of 2D video analyses in determining knee F_A during dynamic movements contributes to previous research implementing the same method in characterizing the lower extremity in the frontal plane during side step (15), drop landing and step landing tasks (46). In this manner, the screening of knee F_A after ACL-injury using 2D video analyses may be a valuable clinical tool. Further characterization the movement patterns demonstrated by healthy limbs during landing may provide new approaches for ACL-injury rehabilitation and endpoint determinations using biomechanical descriptors such as fluency.

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HIGHLIGHTS

- Anterior cruciate ligament-injured athletes executed dynamic movement trials.
- Knee fluency during landing was calculated for injured and uninjured limbs.
- A stepwise trend in knee fluency between trials was recorded for injured limbs.
- Variable landing strategies were observed in unilateral trials for injured limbs.
- Knee fluency may be a valuable parameter to assess in injury rehabilitation.

Figure 1. Polynomial Fit for Raw Velocity Data

Involved (A) and uninvolved (B) polynomial fit for knee joint center velocity data for COD trials. Fluent events were tabulated as the real, unique roots of the polynomial, displayed as red circles below, and visually confirmed for each trial.

Figure 2. Medio-lateral Knee Movement Range for Involved and Uninvolved Limbs: Grouped by Dynamic Movement Trial

Medio-lateral knee joint center range for involved and uninvolved subjects during SLD, COD, and DVJ dynamic movement tasks, centered on zero. Positive and negative values denote medial and lateral knee joint center displacement, respectively. A *** indicates a significant difference between involved and uninvolved limbs ($p < 0.05$).

Figure 3. Medial and Lateral Knee Displacement for Involved and Uninvolved Limbs: Grouped by Dynamic Movement Trial

Independent medial and lateral knee displacement measurements for involved and uninvolved limbs during SLD, COD, and DVJ dynamic movement tasks. Positive and negative values denote medial and lateral knee joint center displacement, respectively.

Figure 4. Analytical Fluency for Involved and Uninvolved Limbs

Analytical fluency values for involved and uninvolved limbs during SLD, COD, and DVJ dynamic movement tests. A *** indicates a significant difference in analytical fluency between limbs ($p < 0.05$).

Figure 5. Involved and Uninvolved Limb Analytical Fluency
Analytical fluency grouped by limb status for SLD, COD, and DVJ dynamic movement trials. A *** indicates a significant difference in analytical fluency ($p < 0.05$).

Table 1

Medio-lateral Knee Velocities

	Average Knee Velocity (m/s)	Uninvolved Limb	P value	Maximum Knee Velocity (m/s)	Uninvolved Limb	P value
	Involved Limb			Involved Limb		
SLD	0.3411 (SD 0.079)	0.3433 (SD 0.077)	0.8369	1.0771 (SD 0.271)	1.1654 (SD 0.412)	0.1651
COD	0.4445 (SD 0.085)	0.4624 (SD 0.099)	0.1562	1.7330 (SD 0.536)	1.8048 (SD 0.511)	0.4574
DVJ	0.3209 (SD 0.087)	0.3103 (SD 0.095)	0.4081	1.0628 (SD 0.335)	0.9862 (SD 0.220)	0.1418