CLASSIFICATION OF HEALTHY LIMB LOADING DURING RUNNING IN POST ANTERIOR CRUCIATE LIGAMENT INDIVIDUALS

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The purpose of this study was to identify and evaluate the effectiveness of new gait metrics to dynamically assess healthy limb performance in post anterior cruciate ligament reconstruction (ACLR) individuals. Metrics comparing the active-to-impact peaks (AIP) ratio and late-to-mid knee flexion angle (LMKF) ratio were extracted from the vertical ground reaction force and knee flexion angle waveforms, respectively, to identify healthy limb loading dynamics during running. One variable binary logistic model was used to model healthy limb loading based on the AIP and LMKF metrics. The metrics successfully aided in the delineation between healthy and pathological movement dynamics. These findings are important because it identifies new metrics that are not dependent on the performance of the individuals non-reconstructed limb to quantify their reconstructed limb function.

KEYWORDS: return-to-sport, performance criteria, modelling.

INTRODUCTION: A goal for many of the 250,000 individuals who suffer from an anterior cruciate ligament (ACL) injury each year in the United States is to return to playing sports (Adams et al. 2012; Boden et al. 2000). Clearance for returning to sport is often based on meeting established return-to-sport (RTS) criteria. Limb symmetry index (LSI) is an established method for assessing the performance of a post-anterior cruciate ligament reconstruction (ACLR) individuals reconstructed limb by comparing it to its non-reconstructed limb (Rohman et al. 2015). This ratio comparing the reconstructed and non-reconstructed limb is advantageous because it is a dimensionless value that allows researchers and clinicians to easily compare results across individuals. Additionally, it is beneficial because the limb symmetry performance assessment can be used to evaluate how the reconstructed limb compares to the non-reconstructed limb across a multitude of hop and balance tasks and is even effective in evaluating limb strength. However, a limitation of LSI is that it is dependent on the comparison between the reconstructed and non-reconstructed limb. This is potentially problematic as the non-reconstructed limb may have been the individual’s weaker limb and comparing the reconstructed limbs strength and performance can leave it at a deficit.

Therefore, this study sought to investigate alternate methods to evaluate healthy limb performance in post-ACLR individuals. We recognize that unresolved neuromuscular impairments in post-ACLR individuals often manifest as changes in vertical ground reaction force (vGRF) production and sagittal plane knee flexion, particularly during running. Running places greater demand on the reconstructed limb to support the body as high loads are exerted on the limb. To minimize the loads placed on the limb, post-ACLR individuals adopt a stiff limb loading strategy to dampen the transmission of the forces (Hurd et al. 2007). These changes can be captured by evaluating vGRF peaks and knee flexion at mid to late stance as these measures can be indicative of how the limb is loading during the stance phase of running. Here, we will develop and investigate new limb loading ratios derived from the vGRF and knee flexion waveforms to serve as new metrics for evaluating healthy limb loading performance. We hypothesize that metrics that compare the active-to-impact peak (AIP) ratio and the ratio of late-to-mid knee flexion angles extracted from vGRF and knee flexion angle waveforms respectively, will accurately identify healthy and pathological limb loading dynamics.

METHODS: Seventeen post-ACLR individuals (mean ± standard deviation; age: 20.4 ± 6.2 yrs; height: 1.8 ± 0.1 m; mass: 71.7 ± 11.1 kg; running speed: 2.7 ± 0.3 m/s): 6.4 ± 1.8; 10 males and 7 females) and 17 healthy controls (age: 20.9 ± 3.4 yrs; height: 1.7 ± 0.1 m; mass: 65.2 ± 13.8 kg; running speed: 2.7 ± 0.4 m/s) performed a running protocol. Each participant provided written informed consent prior to participating in the study. The post-ACLR participants were all 6 months after surgery and were cleared to return to sport by their physician. Each participant received either a bone-patellar-bone or hamstring graft and the surgeries were performed by physicians from the same orthopaedic practice. The control participants had no history of knee surgery and had been injury free for the last 6 months.

Participants performed a running protocol where they were asked to run at a self-selected speed for one-minute on an instrumented treadmill following a 4-minute warm-up jog to get acclimated to the treadmill (Bertec Corporation, Columbus, Ohio). All participants wore the same WR662 sneakers (New Balance, Brighton, MA). A 10-camera motion capture system was used to track marker trajectories (Motion Analysis Corp., Santa Rose, USA). A 56 retroreflective marker set of anatomical and tracking markers were placed on the individuals upper and lower extremities based on an established design (Noehren et al. 2014). Marker data was collected at 200 Hz and was low pass filtered at 8Hz using a zero lag 4th order Butterworth filter. Functional joint centers and inverse kinematics were calculated in Visual3D. Joint angles were derived using an X-Y-Z Cardan angle sequence where the distal segments were assessed with respect to the proximal. Ground reaction force (GRF) data was synchronously measured along with the marker data. The GRF data was collected at 1200 Hz. A zero-lag, 4th order Butterworth filter with a 35 Hz cutoff frequency was applied to the data.

A waveform consisting of consecutive vertical ground reaction force (vGRF) strides was extracted for each participant. For the controls, the waveform was constructed from their right limb and the waveform was constructed from their reconstructed limb for the post-ACLR participants. To construct the active-to-impact peak (AIP) ratio, the active peak and impact peaks for each stride were extracted and the active peak was divided by the impact peak. Similarly, a waveform consisting of consecutive sagittal plane knee kinematic strides were collected for each participant. Then the knee flexion angle at the end of stance was divided by the knee flexion at midstance to create the late-to-mid stance knee flexion angle (LMKF) ratio.

A t-test was conducted to compare differences in mean age, height, mass, running speed, Tegner score, and AIP and LMKF ratios between the control and post-ACLR groups.

A one predictor variable binary logistic regression models were used to assess the AIP and LMKF ratios as indicators of healthy motor function.

Table 1. Comparison of participant demographics. (mean ± standard deviation)

Variable	Control Group	Post-ACLR Group	P-Value
Age (yrs)	20.9 ± 3.4	20.4 ± 6.2	0.69
Height (m)	1.7 ± 0.1	1.8 ± 0.1	0.15
Mass (kg)	65.2 ± 13.8	71.7 ± 11.1	0.08
Speed (m/s)	2.7 ± 0.4	2.7 ± 0.3	0.80
Tegner	6.9 ± 1.3	6.4 ± 1.8	0.28
AIP ratio	1.6 ± 0.1	1.2 ± 0.1	<0.001
LMKF ratio	3.7 ± 1.2	2.1 ± 0.6	<0.001

RESULTS: There were no significant differences in age, height, mass, running, speed and Tegner scores between the Control and post-ACLR groups at significance level 0.05 (Table 1). There were significant differences in AIP and LMKF between the Control and Post-ACLR groups (Table 1). Both the AIP and LMKF ratios are significantly larger in the Control group.

An AIP ratio greater than one indicates that greater force is exerted on the limb during the later stages of stance phase than during initial contact. Here the mean controls AIP was 1.6 ± 0.1 compared to 1.2 ± 0.1 in the post-ACLR individuals. While all participants exerted greater force during late stance phase, the controls exerted roughly 60% more force on their limb during the active peak than the impact peak, compared to a 20% increase in the post-ACLR individuals.

A larger LMKF ratio is representative of greater knee excursion during the mid to late phase of stance. Again, the healthy controls exhibited a larger LMKF ratio (3.7 ± 1.2) compared to the post-ACLR individuals (2.1 ± 0.6) (Table 1). These findings suggest that the healthy controls go through larger knee excursion, including greater knee flexion during mid stance than the post-ACLR individuals. Furthermore, the reduced knee excursion in post-ACLR individuals during the later weight-bearing phase of running as represented by LMKF ratio suggests that the post-ACLR individuals adopt a stiffer running strategy than the healthy controls.

A scatter plot of the AIP ratio against the LMKF ratio demonstrated that the two metrics could be effective in classifying healthy controls and post-ACLR individuals (Fig. 1a). Visual inspection of this scatter plot suggests that an AIP ratio of 1.35 and LMKF ratio of 2.4 could serve as cutoff values to delineate between healthy controls and post-ACLR individuals. A contour plot comparing the two ratios further demonstrated how well the AIP and LMKF can differentiate between the two groups as the color gradient quantified the strength of their association with the healthy limb performance (Fig. 1b). Higher values indicated a stronger association with the control group while lower values indicated a strong association with the post-ACLR group (Fig. 1a). These plots are very useful tools to aid in the visual assessment of healthy and pathological running biomechanics.

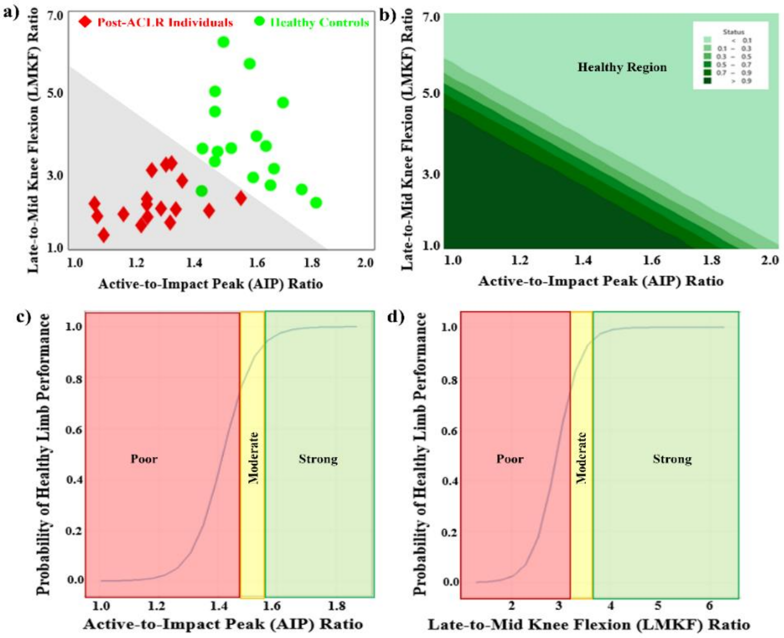

Figure 1: a) Scatter and b) contour plots comparing the AIP and LMKF metrics for the healthy controls and post-ACLR individuals. Plots of the binary logistic regression models for the c) AIP and d) LMKF ratios, respectively. Here the green denotes region of strong healthy limb performance (probability ≥ 0.9), yellow indicates moderate limb performance (0.75 ≤ Probability < 0.9), and red indicates poor limb performance (probability < 0.75).

One predictor variable binary logistic models were generated using the AIP and LMKF ratios. Both models that utilized the AIP and LMKF ratios independently performed well and allowed us to quantify the probability of an individual exhibiting healthy limb dynamics (Table 2).

Table 2. Comparison of Active-to-Impact Peak (AIP) and Late-to-Mid Stance Knee Flexion Model Performance

AIP Logit Model Parameters	
Constant Term	28.8
AIP Term	-20.2
R-squared	67.4%
ROC	0.97
Odds Ratio (0.1 unit change)	7.54

LMKF Logit Model Parameters	
Constant Term	7.2
LMKF Term	-2.6
R-squared	46.0%
ROC	0.92
Odds Ratio (0.1 unit change)	0.77

We defined ranges for low (red), moderate (yellow) and high (green) likelihood of healthy running biomechanics (Fig. 1 c-d). This is advantageous as it can allow clinicians to quickly determine who is ready to return-to-sport. And the odds ratio can help clinicians provide patients with a quantifiable change that should be reached to achieve healthy biomechanics.

DISCUSSION: The objective of this study was to determine if the AIP and LMKF ratios were effective in evaluating healthy limb performance. The results supported the hypothesis as the logistic models were able to determine the likelihood of exhibiting healthy limb dynamics based on individuals AIP and LMKF ratios. Like the LSI, the proposed AIP and LMKF ratios are dimensionless values, which will allow for these metrics to be used to easily compare performance across individuals in both laboratory and clinical settings.

The metrics were successful in delineating between healthy and pathological running biomechanics. Here, the AIP and LMKF ratios served to differentiate between strong, moderate, and poor limb performance. Myer et al. (2011) employed a similar approach where they utilized logistic regression analysis to assess ACL injury risk based on knee abduction moment (KAM). That study divided individuals into high and low injury risk based on a KAM of 25.25 Nm. Like Myer et al. (2011) the AIP and LMKF values at 0.9 and 0.75 probabilities can serve to classify and define ranges of healthy and pathological running biomechanics.

The significantly smaller AIP and LMKF ratios suggests that the post-ACLR individuals likely adopted a stiffer limb loading strategy due to lingering motor deficits following ACLR surgery. Post-ACLR individuals often adopt a stiffer knee loading strategy to attenuate the forces exerted on the limb during running (Hurd et al. 2007; Morgan et al. 2014). Yet, it has been shown that dynamic limb stiffness, particularly knee stiffness, during running is associated with detrimental knee loading in post-ACLR individuals thus highlighting the problem of this limb loading approach (Owen et al. 2023). While it is not clear if they adopted this strategy because they lacked the strength to support the limb during the dynamics task or it reflected fear in placing high loads on the limb, the difference in limb loading dynamics identified by these metrics suggest they could be useful as a return-to-sport criteria. Future work will investigate how to use these and other metrics to classify healthy limb loading in post-ACLR individuals.

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