Empirical Based Modeling for the Assessment of Dynamic Knee Stability: Implications for Anterior Cruciate Ligament Injury Risk

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Abstract— **Anterior cruciate ligament (ACL) injuries are common sports injuries, costing the U.S. roughly $1 billion annually. To better understand the underlying injury mechanism, Nyquist and Bode stability criteria were applied to assess frontal plane dynamic knee stability among male Australian Football players during the weight-acceptance phase of single-leg jump landing. Out of 30 landings, 19 were classified as stable and 11 as unstable. Medial and lateral vasti, hamstring and gastrocnemii muscle activation waveforms were analyzed in parallel to determine if individuals with stable and unstable frontal plane joint biomechanics possessed different lower limb neuromuscular strategies. The total quadriceps muscle activation during the stable landings were significantly higher (p=0.02) than during the unstable landings. Additionally, the vasti exhibited a medial dominance during the stable landings compared to the unstable (p=0.06). These results suggest that individuals with unstable frontal plane knee landing mechanics may have reduced recruitment of the muscles crossing the knee; specifically, the medial muscles, which could limit their ability to compress and support the joint. The stability criteria were able to classify stable and unstable knee mechanics. And the differences in muscle activation during these stable and unstable landings provided new insights towards the ACL injury mechanism and possible injury prevention countermeasures.**

I. Introduction

Anterior cruciate ligament (ACL) injuries are common sports injuries that impact 1 in every 3,000 individuals [1]. An ACL injury results in the loss of both translational and rotational knee stability for the successful execution of dynamic movements like single-leg jump landing [2]. Furthermore, the appropriate activation of the muscles crossing the knee have the capacity to reduce the loads applied to the ACL while supporting and stabilizing the knee [3,4]. Researchers have implemented injury prevention protocols focused on altering muscle function; yet ACL injury rates continue to increase [3]. To help change this observed trend in the literature, a better understanding of the relationship between dynamic knee stability and muscle function is needed.

Dynamic knee stability assessments evaluating an individual during movement tasks; such as running, cutting and jumping, are used to determine an athlete's ability to return-to-sport following an ACL injury [5]. These dynamic assessments are better indicators of knee stability than static assessments because they analyze how an individual's knee responds under variable loading. Maximum knee abduction moment (KAM) during the weight-acceptance (WA) phase (first 20-30% of stance), are analyzed as it is often associated with ACL injury risk [6,7]. Maximum KAM is an important knee loading variable, however when analyzed in isolation does not fully assess the time varying characteristics of knee stability. Therefore, investigating the entire waveform to identify certain characteristics (e.g., oscillatory behavior) of a system may provide important insights into the individuals underlying dynamic knee stability and injury risk [8].

Previous work has assessed and quantified dynamic gait stability via techniques like Lyapunov exponents [9-11]. These approaches represent empirical-based modeling (EBM) as they derive a model of a system from experimental data. This study will employ EBM by using experimental KAM and ground reaction force (GRF) waveform data to develop a transfer function to evaluate dynamic knee stability via Nyquist and Bode stability analyses. While these techniques are relatively new to biomechanics, they have successfully evaluated differences in knee stability in individuals who had and had not suffered a knee injury [12].

Poor muscle coordination, manifesting as reduced hamstring activation and medial-lateral muscle imbalances, have been associated with elevated ACL injury risk, particularly in the form of increased frontal plane joint oscillations [6]. Thus, poor KAM biomechanics could highlight the muscles inability to control the knee movement and body segment positions both proximal and distal to the joint. This study will investigate the neuromuscular activation of muscles crossing the knee during stable and unstable single-leg landings to better understand muscle coordination as a function of dynamic knee joint stability.

The objectives of this study are to use EBM to assess and quantify dynamic knee stability from KAM and GRF waveforms in male Australian Football players during the WA phase of single-leg jump landing and to identify muscle activation strategies that are characteristic of stable and unstable landings. It is hypothesized that stable landings will exhibit elevated muscle activation and more balanced medial-lateral vasti, hamstring and gastrocnemii muscle co-contractions. The findings of this study can be used to understand knee mechanics and muscle coordination as they relate to knee ligament injury risk and the underlying ACL injury mechanism.

II. Methods

A Experimental Protocol and Data Collection

Five athletes (age 20 ± 1 years; mass 87.1 ± 5.4kg; height 1.90 ± 0.1m) were selected from the aforementioned cohort

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of Western Australian Amateur Rules Football players to participate in this single-leg jump landing protocol [13]. All of the experimental procedures were approved by the University of Western Australia Human Research Ethics Committee and all participants provided their informed written consent prior to the data collection. These individuals were selected because they exhibited greater lateral trunk lean over the stance leg, an unstable motion, than the participants from the larger cohort of thirty-four individuals. Six trials per participant, including two trials for each of the three ball swing directions (medial, lateral, or central), were analyzed for a total of 30 landing trials [14]. The goal of the different ball swing directions was to further destabilize the individuals in addition to the single-leg jump landing task. For the single-leg jump landing protocol, participants jumped from their preferred leg and while in flight, grabbed an Australian football that was randomly swung medially, laterally or held central to the participants' approach directions before landing on the force platform with their takeoff leg, the right leg for all participants (Fig. 1) [15]. The jump height was assessed by having each participant perform three jumps to determine their maximum, which included their reach, and then the ball was placed at approximately 90% of that maximal vertical jump height. The maximal vertical jump height was not recorded.

Experimental kinematic marker trajectories, GRFs, and surface electromyography (sEMG) data were collected from each participant during the single-leg jump landing task. Kinematic marker trajectories were obtained from fifty-six upper- and lower-body retro-reflective markers. A complete description of the marker locations has been previously described and shown [15]. Three-dimensional, full-body kinematics were recorded using a 12-camera, 250 Hz VICON MX motion capture system (Oxford Metrics Ltd., UK) [14,15]. The GRF data were synchronously recorded at 2,000 Hz using a 1.2 x 1.2m AMTI force platform (Advanced Mechanical Technology Inc., Watertown, MA). Both the kinematic and GRF data were low-pass filtered at 20 Hz using a zero phase-shift 4th-order Butterworth digital filter in Workstation. Joint angles and moments were computed via inverse kinematics and residual reduction analysis in OpenSim 1.9.1 [16].

The sEMG data for six muscles: vastus medialis, vastus lateralis, medial and lateral hamstrings, medial and lateral gastrocnemii were collected at 1,500 Hz. The vastus medialis and vastus lateralis muscles were measured to represent the vasti muscles. The raw experimental sEMG data were filtered with a zero phase-shift 4th-order Butterworth filter between 30 and 500 Hz, full wave rectified and then low-pass filtered using a zero phase-shift 4th-order Butterworth digital filter at 6 Hz to create linear envelopes. Following linear enveloping, peak muscle activation was obtained from measuring muscle activation during dynamical and functional tasks for each muscle. The peak muscle activation was used to normalize each muscle's sEMG signal to 100% activation. The result is an sEMG waveform from zero to full activation which is 1. Frontal plane knee kinetics were analyzed during the weight-acceptance phase of landing because this is when knee valgus moments acting on the knee are the highest and thought to be when the ligament is at the greatest risk of injury [14,15].

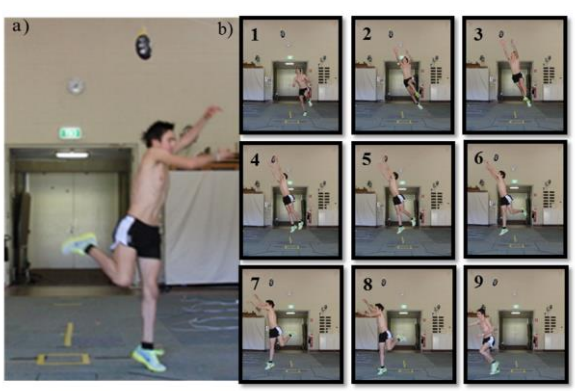

Figure 1. Series of images of an individual performing the experimental single-leg jump landing protocol in the laboratory.

B. Empirical Based Modeling and Stability Analysis

Nyquist and Bode stability analyses were used to assess frontal plane dynamic knee stability from the KAM and GRF data waveforms and classify participant trials as stable and unstable. The system or knee was represented as a transfer function. The transfer function is a ratio of an output response to an input perturbation in the frequency domain [8,17]. Here the input was the vertical GRF and the output response was the KAM waveform (Eq .1). These waveforms were converted from the time to frequency domain using Fourier transform. The generation of a transfer function in this manner has been used previously [12,18]

$$Transfer\ Function = \frac{frontal\ plane\ knee\ kinetic\ waveform}{ground\ reaction\ force\ waveform} \quad (1)$$

The Nyquist stability criterion employs Cauchy's theorem that maps the transfer function into the complex plane [8]. This theorem determines stability based on the number and location of poles, the values that cause the denominator of the transfer function to equal zero, that reside in the right half of the complex plane and the encirclement of the point (-1,0) (Fig. 2). When no poles are present in the right half plane, and if (-1,0) was not encircled, the system was stable; otherwise it was unstable (Fig. 2) [8]. The Bode stability criterion approach computes the gain and phase margins of the system (Fig. 2). The stability of the resulting gain and phase margins are based on their sign and displacement from zero. Waveforms were classified as stable if both the gain and phase margins were positive; otherwise it was unstable (Fig. 2). The stability analysis was performed using custom functions in MATLAB (The MathWorks, Inc., Natick, Massachusetts, USA).

C. Muscle Activation Assessment

For both the stable and unstable landing trials, the mean muscle activation, total muscle group activation and the total muscle activation ratio between the medial-lateral vasti, hamstrings and quadriceps groups were calculated. Each muscle's activation was normalized to the peak activation during weight acceptance (%MVC) based on the overall peak activation for all of the trials the individual performed. Total muscle activation is the sum of each muscle's peak activation. These values were calculated for select muscles crossing the knee and reported for each of vasti, hamstrings,

and gastrocnemii muscle groups. The ratio of the total muscle activation between the medial-lateral vasti, hamstrings and gastrocnemii were computed by dividing the total activation of medial muscle to the lateral muscle, respectively. The sEMG analyses were performed using a custom MATLAB code (MATLAB R2012a, The MathWorks, Inc., Natick Massachusetts, USA).

D. Statistical Comparison of Stable and Unstable Waveforms

Two-sample *t*-tests were performed to test the hypotheses of the equality of the means for the gain margin, phase margin, and maximum KAM data. A two-sided significance level of 0.05 was used for all statistical tests. Two-sample *t*-tests were also performed to test the hypotheses of the equality of the means for the sEMG individual muscle activation mean, group total and total medial-lateral muscle activation ratio data for the stable and unstable trials (α=0.05). All statistical analyses were conducted in Minitab (Minitab Inc., State College, Pennsylvania, USA).

III. Results

Nineteen single-leg jump landing trials exhibited stable frontal plane joint kinetics and eleven trials had unstable kinetics based on the stability analyses of the KAM waveforms (Fig. 3). The unstable trials generated gain margins of -63.1 ± 29.4dB (mean ± standard deviation), which was significantly lower than the 109.9 ± 234.8dB the stable trials reported (p=0.03). The unstable phase margins of -17.4 ± 96.5° which were significantly lower (p<0.01) than the stable trials' phase margins of 67.8 ± 34.5° (Table 1). The unstable trials' reported maximum KAM of 1.4 ± 0.5 Nm/kg (Table 1). Although higher, it was not significant.

Each muscle but the lateral hamstrings produced higher mean muscle activation than during the stable trials. The medial and lateral vasti reported significantly higher mean muscle activation (Table 2). The mean muscle activation for the vastus medialis was 0.46 ± 0.14 for the stable landings and 0.34 ± 0.08 (p=0.04) for the unstable. Mean vastus lateralis activation was 0.39 ± 0.11 for the stable trials and 0.28 ± 0.05 (p=0.02) for unstable trials.

The quadriceps produced the largest total muscle activation, followed by the gastrocnemii and then the hamstrings for both the stable and unstable groups. The quadriceps exhibited significantly larger total mean muscle activation during the stable landings (85.5 ± 22.7) compared to the unstable landings (62.5 ± 11.6; p=0.02) (Table 3). That difference was significant (p=0.02). No other total mean differences were significant.

The ratio of medial-lateral hamstring muscle activations indicated greater medial hamstring activation during stable landings (Table 3). None of the medial-lateral muscle activation ratios were significantly different between the stable and unstable trials.

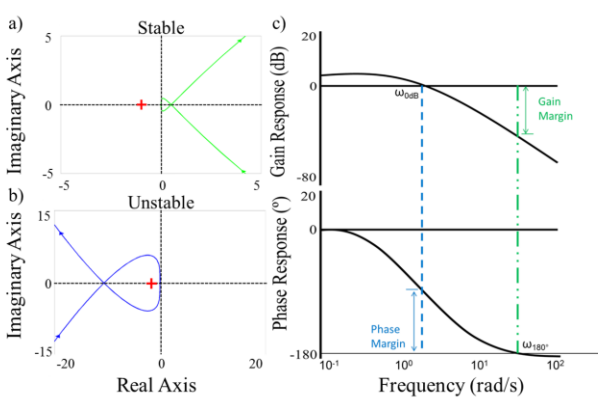

Figure 2. Nyquist and Bode stability plots for stable and unstable joint biomechanics. a) Nyquist stability plot for stable joint biomechanics. b) Nyquist stability plot for unstable joint biomechanics. c) Bode diagrams of the gain and phase margin plots analyzed for stability analysis. The gain margin is computed by identifying the frequency ($\omega_{180°}$) where the phase response intersects at -180° and finding the gain that corresponds with that frequency (denoted by the dotted dashed line). Similarly, the phase response is calculated by finding the frequency where the gain response intersects with 0db and identifying the corresponding gain (denoted by the dashed line).

TABLE I. Comparison of Gain Margins, Phase Margins and Knee Abduction Moments for stable and unstable landings.

Variable	Stable	Unstable	p-Value
Gain Margin (dB)	109.9 ± 234.8	-63.1 ± 29.4	0.03*
Phase Margin (°)	67.8 ± 34.5	17.4 ± 96.5	<0.001*
Knee Abduction Moment (Nm/kg)	1.2 ± 0.8	1.4 ± 0.5	0.61

TABLE II. Comparison of normalized mean medial and lateral vasti, hamstrings, gastrocnemii muscle activations for the stable (N=19) and unstable (N=11) landings.

Muscle	Stable	Unstable	p-Value
Vastus Medialis	0.46 ± 0.14	0.34 ± 0.08	0.04*
Vastus Lateralis	0.39 ± 0.11	0.28 ± 0.05	0.02*
Medial Hamstring	0.31 ± 0.25	0.19 ± 0.16	0.25
Lateral Hamstring	0.15 ± 0.06	0.17 ± 0.04	0.26
Medial Gastrocnemius	0.37 ± 0.14	0.30 ± 0.13	0.31
Lateral Gastrocnemius	0.35 ± 0.19	0.23 ± 0.07	0.14

TABLE III. Comparison of normalized total quadriceps, hamstrings, gastrocnemii and the total medial-lateral vasti, hamstrings and gastrocnemii muscle ratios for the stable (N=19) and unstable (N=11) landings.

Group	Stable	Unstable	p-Value
Quadriceps	85.5 ± 22.7	62.5 ± 11.6	0.02*
Hamstrings	45.7 ± 28.0	36.7 ± 19.4	0.44
Gastrocnemii	71.3 ± 32.5	53.4 ± 20.1	0.18
Flexors	117.0 ± 59.9	90.0 ± 37.0	0.28
Medial/Lateral Vasti	1.2 ± 0.3	1.2 ± 0.3	0.97
Medial/Lateral Hamstrings	2.0 ± 1.3	1.0 ± 0.7	0.06
Medial/Lateral Gastrocnemii	1.2 ± 0.4	1.3 ± 0.3	0.46

IV. Discussion

The objective of the study was to classify and quantify dynamic knee stability in male Australian Rules Football players during the WA phase of single-leg jump landing and to identify differences in muscle activation strategies between the stable and unstable trials. Nineteen trials were classified as stable and 11 as unable via the Nyquist and Bode stability analyses. Stable trials produced greater overall muscle activation with the quadriceps producing significantly greater mean and total activation than during

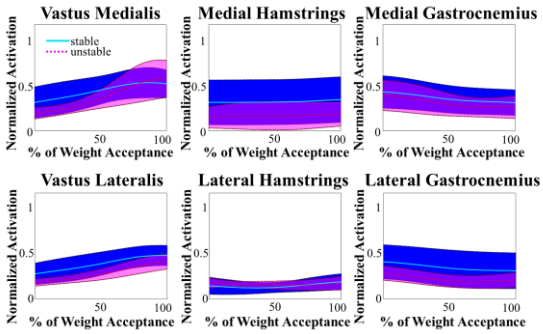

Figure 3. Comparison of the mean normalized experimental surface electromyography (sEMG) data across the stable (n=19) and unstable groups (n=11) for the six muscles crossing the knee

the unstable trials. Unstable jump landing trials were also characterized by reduced medial hamstring activation compared to the lateral hamstring. These findings indicate the stable trials were defined by greater quadriceps and medial hamstring muscle activation.

The combination of the EBM and Nyquist and Bode stability analyses were able to differentiate between stable and unstable jump landing trials. Sixty-three percent of the trials were deemed stable while 37% were classified as unstable. Individuals exhibited both stable and unstable jump landing biomechanics, which is reasonable as this population was selected because they exhibited greater lateral trunk lean, an unstable behavior, during the jump landing task. Here unstable biomechanics do not indicate immediate injury but rather the potential for injury. Moreover, repetitive unstable trials could identify individuals who are at greater risk for injury. While the application of the Nyquist and Bode stability analyses are still new to biomechanics, they serve as another tool that researchers may use to investigate joint stability.

Muscles function to stabilize the knee during dynamic tasks through coordinated muscle activation [19,20]. While muscle activation is not linearly/directly related to force, the greater muscle activation during the stable trials could represent an attempt to stabilize the knee via joint compression. The increased activation of both the knee flexors (hamstrings and gastrocnemii) and extensors (vasti) supports the literature that these two groups function synergistically to stabilize the knee via joint compression [21]. This study's findings suggest that during the stable landings, individuals adopted a protective mechanism.

A secondary finding of the study was the reduced medial hamstring activation in the unstable trials. Strong medial muscle force and/or activation; specifically, by the hamstring muscles, is associated with stable knee biomechanics [3,7]. Previous studies have indicated the medial muscles can provide the necessary support for valgus loads [3,22]. The increased medial muscle activation observed in the stable trials indicates a more optimal muscle activation strategy to support the knee and reduce ACL injury risk.

A limitation of this study was that we analyzed male athletes and not female athletes since females tear their ACL at a higher rate than males. The objective of this study was to identify stable and unstable joint waveform characteristics and associated muscle activation strategies during a single-leg jump landing task. We expect that both females and males have the same goal of stabilizing their knee's during landing. Thus, the joint and muscle activation strategies adopted by the males in this study during stable trials could be used to help identify potentially beneficial joint biomechanics and muscle activation strategies.

V. Conclusion

Our research provides new insights by quantifying dynamic knee stability using the KAM and GRF waveforms to identify differences in muscle activation strategy in stable and unstable single-leg jump landing trials. The muscle activation strategy observed during stable trials indicates that individuals attempted to stabilize the knee via joint compression and reduced valgus loading. This unique stability assessment methodology provided additional insight into the cause-and-effect relationship between the musculoskeletal and neuromuscular systems that should be applied to developing ACL screening tools and muscle targeted training protocols for at-risk individuals. Future work will investigate how well the Nyquist and Bode stability criteria will differentiate between stable and unstable resultant knee waveforms, which are comprised of the knee waveforms from all three planes, in individuals during different tasks such as walking and running.

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