Hysteresis and Dissipation Coefficient in Recreational Athletes with Chronic Ankle Instability Compared to Controls

by
Trenton Joiner

A THESIS

submitted to

Oregon State University

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degree of

Honors Baccalaureate of Science in Bioengineering
(Honors Scholar)

Presented August 26, 2020
Commencement June 2021

AN ABSTRACT OF THE THESIS OF

Trenton Joiner for the degree of Honors Baccalaureate of Science in Bioengineering presented on August 26, 2020. Title: Hysteresis and Dissipation Coefficient in Recreational Athletes with Chronic Ankle Instability Compared to Controls.

Abstract approved:____

Cathleen Crowell

Ligaments serve to control the movements of bones and joints within the body. Viscoelastic properties, such as hysteresis, allow them to perform their functions; however, these properties may change following injury. Understanding alterations in viscoelastic properties may be useful in diagnosing, tracking, and determining treatment effectiveness in Chronic Ankle Instability (CAI). The purpose of this study was to determine if hysteresis and dissipation coefficient (DC) were altered in recreational athletes with CAI compared to uninjured controls. An instrumented anterior drawer test was applied, and the loading and unloading curves were used to calculate hysteresis and DC. Hysteresis was significantly lower in the CAI group compared to the controls, but DC was not. Individuals with CAI may be less able to absorb and restitute energy associated with physiologic loading than controls, which may perpetuate episodes of giving way at the ankle. Future research should determine if hysteresis and DC are sensitive to CAI and responsive following treatment or rehabilitation intervention.

Key Words: viscoelastic property, energy absorption, ankle ligament complex, dissipation

Corresponding e-mail address: joinertr@oregonstate.edu

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APPROVED:

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Cathleen Crowell, Mentor, representing School of Biological and Population Health Sciences

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Sam Johnson, Committee Member, representing School of Biological and Population Health Sciences

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Skip Rochefort, Committee Member, representing School of Chemical, Biological, and Environmental Engineering

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Toni Doolen, Dean, Oregon State University Honors College

I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Trenton Joiner, Author

Introduction

Ligaments are fibrous, viscoelastic tissues that connect bones, limit their movement, and keep them aligned (Solomonow). Within joint complexes, ligaments work in combination with bones, muscles, tendons, and cartilage to influence and control the movement of the body. Ligaments work by lengthening and increasing tension to hold bones and joints within a healthy range of motion during movement (Solomonow). Ligaments have viscoelastic properties that allow them to function correctly, including length-tension relationship, creep, tension-relaxation, strain rate, and hysteresis. Under an increasing load, more ligament fibers are used with minimally increased tension until the ligament is fully engaged. At full engagement, the tension in the ligament increases exponentially in a response known as the length-tension relationship. The tension-relaxation phenomenon describes the continued lengthening of a ligament over time in response to a constant load. The ligament will continue to lengthen over time under that constant load, and this additional lengthening is known as creep (Solomonow). Ligament response to load can be affected by the strain rate, or rate of elongation of the ligament. Hysteresis is a significant viscoelastic property of ligaments (Solomonow). Hysteresis is defined as the difference between energy absorption and energy restitution in the ligament during loading and unloading, respectively. All these properties described allow ligaments to lengthen and tense under load and return to their original length after unloading. Unfortunately, injuries to the ligaments may alter these tissue properties and relationships (Lin, Shau and Wang).

Ligament sprains are caused by the overstretching and/or tearing of the ligaments due to tensile forces placed on the ligament that exceed its physiological limits (Kelc, Jakob and Matevz). Sprains to the ligaments that are a part of the Lateral Ankle Joint Complex are among the most common injury in sports (Lin, Shau and Wang). If these sprains are not correctly diagnosed and treated, over time they frequently develop into chronic ankle instability (CAI) (Lin, Kang and Wang) (Malmir, Olayei and Talebian). CAI is associated with decreased levels of physical activity and reduced health-related quality of life (Lin, Kang and Wang). CAI is generally considered to include a continuum of mechanical ankle instability (MAI) and functional ankle instability (FAI) (Lin, Kang and Wang). MAI is laxity caused by the limitations of the anatomic structures of the joint, while FAI is related to the patient's subjective perception of their symptoms as related to the joint.

Traditionally, injury assessments for lateral ankle sprains have been subjective, such as the commonly used manual anterior drawer test (Lin, Shau and Wang). However, while this test provides some subjective indication of ligament laxity, it does not reveal other tissue properties. Some characteristics, such as laxity and stiffness, have been suspected to be altered in those with CAI, but these properties do not seem to be sensitive enough for diagnostic purposes (Hubbard, Kaminski and Griend). Other stress-time related viscoelastic properties, such as hysteresis, have been shown to potentially aid with injury evaluation, serving as biomarkers to assess injury and healing (Lin, Shau and Wang).

Hysteresis may be a more sensitive indicator of change in viscoelastic properties to the lateral ankle complex after injury. Energy absorption (EA) is the area under the load-displacement curve, denoting how the ligament stretches during load application. Energy restitution (ER), conversely, is the area under the load-displacement curve during unloading, or how the ligament returns to a resting state as the load is removed. ER typically has a smaller area under the curve and a different curve shape than EA because some energy is lost in this imperfect system (Figure 1). The difference in area under the EA and ER curves is hysteresis, which represents the amount of energy that was lost between the loading and unloading of the ligaments and is approximately illustrated in Figure 1 by the shaded oval (Kelc, Jakob and Matevz). Because different ligaments may have different curve profiles and responses may change with repeated loading, the dissipation

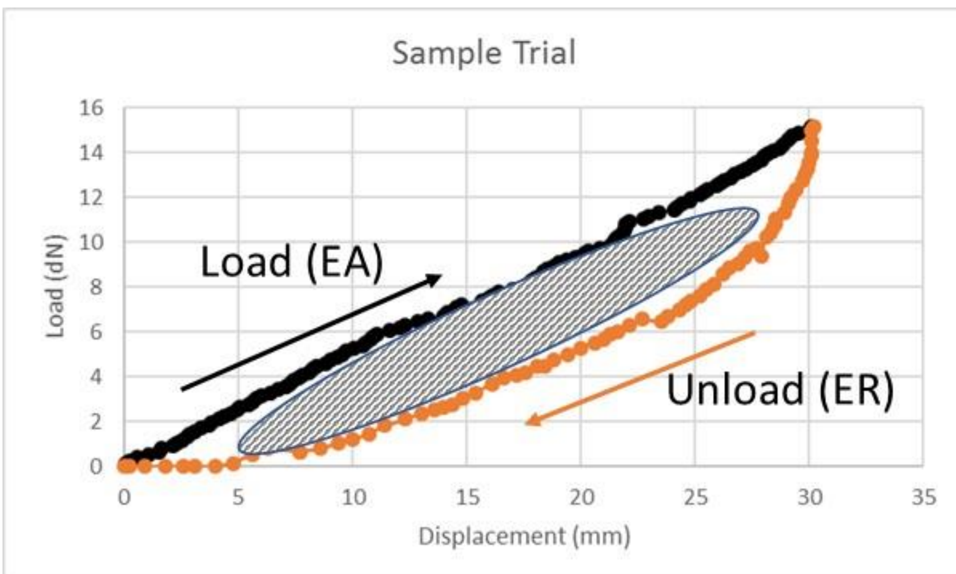

Figure 1: A single loading and unloading curves representing EA and ER.

coefficient (DC) is used to represent the amount of energy lost between loading and unloading, relative to the amount of energy that is originally absorbed (Malmir, Olayei and Talebian). Healthy ligaments must function to resist injury by accommodating load, especially over time and under repeated loading. Having too great of a difference in EA, ER, or hysteresis may play a role in injury occurrence or the development of CAI, as the ligaments may lose their ability to accommodate to and properly dissipate energy (Malmir, Olayei and Talebian).

Limited in-vivo studies have investigated how these properties change after index injury and during the process of healing or development of CAI. The use of an instrumented anterior drawer test allowed for quantitative data to be used to identify viscoelastic properties as biomarkers to assess injury and severity (Lin, Shau and Wang). Relaxation and creep have both been found in previous studies to serve as quality biomarkers for ankle injuries (Lin, Kang and Wang). Our study adds to the work by considering the use of hysteresis as a method for quantifying or characterizing CAI, similar to how other viscoelastic properties have already been applied. Hysteresis may be a key viscoelastic property representing the ability of the lateral ankle complex to respond to accommodate repeated loading, such as loading that occurs over the course of a practice or competition. The purpose of the study was to determine if hysteresis and dissipation coefficient were significantly different among a CAI group compared to a Control group. We hypothesized the CAI group would demonstrate decreased hysteresis and dissipation coefficient, due to the effects of injury.

Methods

Participants and controls in this study were male and female recreational athletes between the ages 18-35 who participated in at least 90 minutes of physical activity weekly. This specific project represented secondary analysis of a different project, thus, no power calculations were completed as it was exploratory work. As such, the local IRB determined this specific project was "exempt," though IRB approval had been sought and granted for the original project. The CAI group had a history of moderate to severe ankle sprains at least 12 months prior to study that required at least 3 days of immobilization and/or non-weight bearing rest. The participants also reported at least 2 episodes of the ankle giving away within the last 12 months before study, and a Cumberland Ankle Instability Tool (CAIT) score of 24 or less out of 30, indicating poor function (Gribble, Delahunt and Bleakley). The control group had no history of ankle sprain, no history of their ankles giving way, and a CAIT score of at least 28, indicating good function. The exclusion criteria for participants included a history of lower extremity surgery or fracture, signs or symptoms of an acute ankle sprain (including swelling, discoloration, heat, or pain), current injury to another lower extremity joint characterized by swelling, discoloration, heat, or pain, pregnancy (associated hormonal changes may affect ligamentous laxity and interfere with screening procedure), and diagnosis of a vestibular disorder or Charcot-Marie-Tooth disorder which could affect test results.

Participants provided informed consent for the original project, completed the CAIT, and underwent testing. An instrumented anterior drawer test was completed with a LigMaster (version 1.26, SportTech Inc., Charlottesville, VA, USA) (Figure 2). The participant was on their side, with their knee flexed 90 degrees and the heel of the test limb fixed and stabilized (Figure 3). A pressure actuator was placed 5mm proximal to the medial malleolus on the anterior tibia and used to apply a measured load from an anterior to posterior direction. A wheel with a handle attached to the back of the actuator was manually rotated at a consistent rate to load and unload the

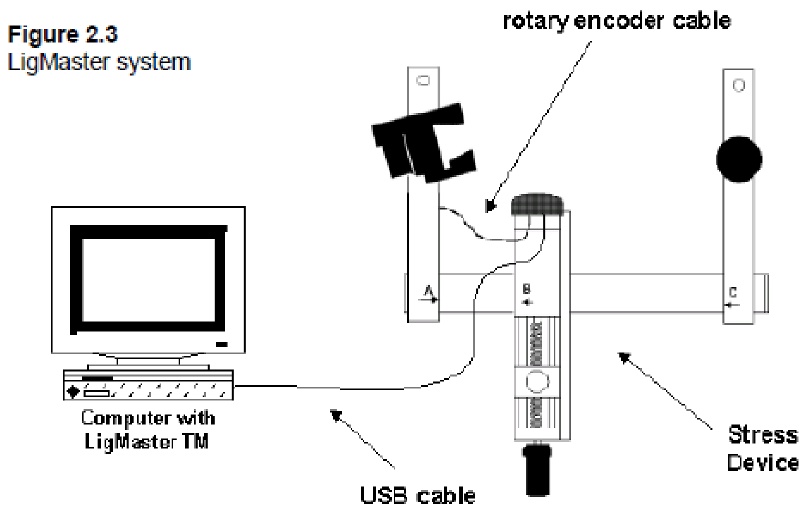

Figure 2: LigMaster setup for the instrumented anterior drawer test

participant's ankle. The displacement of the tibia on the talus was measured in mm. Both load and displacement are captured by the software. The tester reliability was established ahead of testing as >0.8.

To begin the measurement, the participant was placed in the LigMaster with no force applied. The wheel was cranked to apply a force at 2-3 seconds/dN until 15 dN was reached, representing loading. Once 15 dN was reached, the force was released at the same rate of unloading was applied until 0 dN was registered. Three trials on each ankle of each participant were measured, using the last 2 in the calculations of the results. Pilot testing indicated the first trial was not reliable compared to the 2nd and 3rd, and was therefore used as an "accommodation trial."

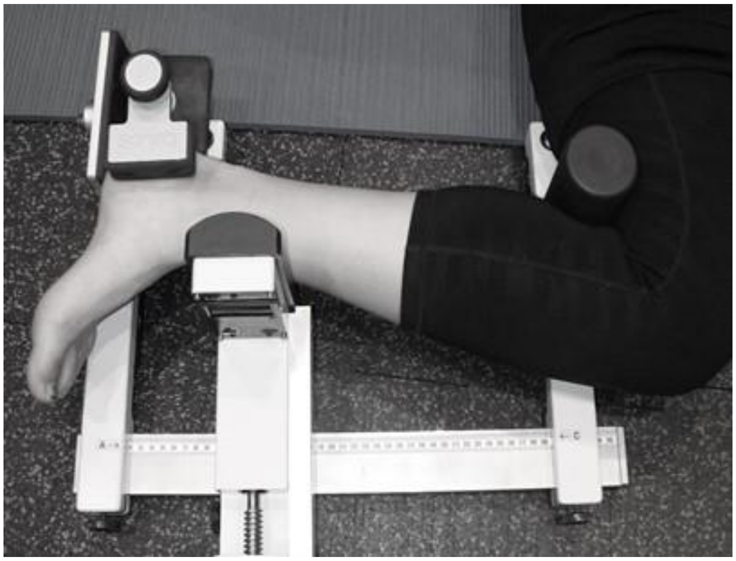

Figure 3: Position of a participant using the Ligmaster testing system

Additionally, pilot testing indicated rate of unloading was consistent across participants across trials and was not considered a factor. The test limb was the lower scoring limb in the CAI participants, and a matched limb in the controls. Loading (EA) and unloading (ER) curves were found using LigMaster software (loading curve) and image analysis of the software output via MATLAB scripts (unloading curve). Commercial grade video (60Hz) of the unloading software output was down-sampled in a 1:22 frame ratio to match the loading curve collection rate. The area under the curves was calculated using the trapezoidal rule in Microsoft Excel, and these values were used to find hysteresis and dissipation coefficient. Hysteresis was defined as the difference between the areas under the Energy Absorption (EA) and energy restitution (ER) curves (Hysteresis = EA – ER). Dissipation coefficient (DC) was hysteresis normalized with EA (DC = [EA-ER]/EA).

Means were calculated across participants and groups. Independent samples t-tests were applied to test for group differences between the CAI participants and the controls. Power and effect size were calculated along with 95% confidence intervals.

Results

Participant demographics are presented in Table 1. The CAI group had 3 males and 11 females, while the control group had 14 males and 11 females. Prior to analysis, hysteresis and dissipation coefficient data were screened for outliers and extreme cases. One participant was excluded out due to extreme values (means > 3 standard deviations [SD] from mean). All other participants' data were retained. There were no statistically significant differences among groups in age, mass, or height, but the CAI group had a statistically significantly lower CAIT score on their test limb ($p<0.001$) as expected. Hysteresis and DC values, along with statistical output, are reported in Table 2.

Table 1: Demographic information of the participants of the study

	Group	**Mean**	**SD**
Age (years)	Controls	22.6	3.2
	CAI	22.5	3.1
Mass (kg)	Controls	70.3	17.8
	CAI	69.0	13.9
Height (cm)	Controls	169.5	7.5
	CAI	165.5	11.2
CAIT test score	Controls	29.3	0.8
	CAI	18.1	5.2

Table 2: Hysteresis and Dissipation Coefficient Means and Statistical Analysis

	Group	Mean	SD	t-value	p-value	Effect Size	Mean % Diff.	Power
Hysteresis (dN*mm)	Controls	83.3	21.6	2.110	0.042	-0.70	17.5%	0.57
	CAI	68.7	19.2					
DC (unitless)	Controls	45.4	6.7	1.747	0.089	-0.59	8.1%	0.46
	CAI	41.7	5.5					

Discussion

Hysteresis for the CAI group was statistically significantly smaller than the controls. There was not a statistically significant difference in DC between the groups. The trending (though not significant) p-value of DC and the relatively large effect size of the hysteresis suggested that hysteresis is reduced in the ligaments due to the CAI, and DC may also be lower, perhaps indicating clinical relevance.

The decreased hysteresis suggests that injuries to the lateral ankle complex and presence of CAI reduced the lateral ankle complex's ability to absorb and dissipate the load placed upon it, which may contribute to complaints of giving way. Previous research indicated both DC and EA decreased over time with repeated loading in uninjured controls (Malmir, Olayei and Talebian). Our study found similar results, but with more acute loading in a CAI population. The CAI population showed decreased hysteresis with acute loading, creating a lower starting position for any repeated loading. CAI populations may follow similar patterns as the Malmir study under repeated loading, such as over the course of a competition or practice. Typically, in uninjured ligaments, hysteresis is demonstrated to shift over repeated loading, moving "down and right" in the torque-angle graph. Malmir et al. (Malmir, Olayei and Talebian) repeated 40 cycles and found EA decreased from 1 to 20 repetitions, plateauing from 20 to 40 repetitions, while DC decreased from 1 to 30 repetitions, and again at 40 repetitions. The authors characterized this response as "protective" against injury, but unable to be sustained indefinitely with repeated or long-term loading. They found a non-linear response to loading, with decreases of ~70% in EA by repetition 15, and ~25% decrease in DC, with 80% occurring before repetition 15 (Malmir, Olayei and Talebian). They reasoned that as tissues absorbed less force, they may be less able to absorb subsequent "shocks" like an injury mechanism. Our data, comparing those with CAI to uninjured controls, demonstrated that CAI already start out as "reduced" in terms of hysteresis, and close to reduced in terms of DC. DC had a lower percentage difference than hysteresis, suggesting that the CAI group's ability to restitute the load possibly decreased more than the ability to absorb the initial load. Malmir et al. suggested that changes in the viscoelastic conditions of the ligaments are what lead to an inability to handle loads properly, resulting in the decrease in EA and DC (Malmir, Olayei and Talebian). Initial decreased viscoelastic properties in CAI populations in addition to likely decreases seen during repeated loading could contribute to a greater risk of injury for CAI participants in competition.

The results of this study may suggest rather than confirm the importance of hysteresis as a diagnostic tool. Hysteresis may be a more sensitive method of providing some objective quantification of the effects of CAI on tissue properties compared to laxity, stiffness, or relaxation (Hubbard, Lin). While the testing methodology used in this study may prove difficult in clinics without the proper equipment and training, there is a potential for better diagnosis of initial injury, CAI status, and tracking of healing and rehabilitation progress. The data collection and processing methods of this study were potentially flawed due to human error, and the small sample size had an impact on the results as well, with lower power in the dissipation coefficient measure. References indicated that the rate of loading of the ligaments during testing was not relevant, but it is possible that this plays a role and may have affected results. The mechanism of loading during the study likely differs from the mechanism of injury. Having a lower loading rate compared to the actual mechanism may have allowed the ligament to be less stiff. The increased stiffness of a ligament in response to a real-world loading rate would likely impact its hysteresis, but the testing equipment was insufficient to replicate this real-world behavior. Additionally, the groups were unbalanced by gender, which may have impacted results. Future research should include a larger sample size, with balanced gender, using the same methodology. An added analysis of how the hysteresis is affected in subjects separated by MAI and FAI would be useful as well. It is also worth exploring whether hysteresis and dissipation coefficient are useful in quantitatively determining ankle sprain severity (i.e. grade), or to track progress of rehabilitation during an athlete's return from injury. Potentially different or better initial treatment and rehabilitation may be able to restore viscoelastic properties after injury, or at least mitigate losses, but that is currently unknown.

Conclusion

CAI is likely caused by a variety of factors, one of which may include changes in viscoelastic properties of the lateral ankle ligament complex (Lin, Kang and Wang). One such property is hysteresis, which represents the energy that is dissipated between the loading and unloading of a force on a ligament (Solomonow). This study suggests that hysteresis is decreased in people with CAI, compared to healthy controls. Inability to absorb and restitute forces during physical activity may perpetuate CAI symptoms. Such a difference in hysteresis may allow for quantitative diagnosis, tracking, and checking the treatment of athletes with CAI. Rehabilitation interventions or better early treatment may be able to restore or maintain these viscoelastic properties. This method may be preferable to measuring laxity or stiffness, which have not shown strong sensitivity to CAI. The results of this study can be used to make suggestions rather than draw conclusions, and future research can expand upon these results to include larger populations and potential grading of CAI.

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