

Relationship Between Tibial Acceleration and Proximal Anterior Tibia Shear Force Across Increasing Jump Distance

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Proximal anterior tibia shear force is a direct loading mechanism of the anterior cruciate ligament (ACL) and is a contributor to ACL strain during injury. Measurement of this force during competition may provide insight into risk factors for ACL injury. Accelerometers may be capable of measuring tibial acceleration during competition. The purpose of this study was to examine the relationship between acceleration measured by a tibia-mounted accelerometer and proximal anterior tibia shear force as measured through inverse dynamics and peak posterior ground reaction forces during two leg stop-jump tasks. Nineteen healthy male subjects performed stop-jump tasks across increasing jump distances. Correlation coefficients were calculated to determine if a relationship exists between accelerometer data and proximal anterior tibia shear force and peak posterior ground reaction force. An analysis of variance was performed to compare these variables across jump distance. Significant correlations were observed between accelerometer data and peak posterior ground reaction force, but none between accelerometer data and proximal anterior tibia shear force. All variables except peak proximal anterior tibia shear force increased significantly as jump distance increased. Overall, results of this study provide initial, positive support for the use of accelerometers as a useful tool for future injury prevention research.

Keywords: noncontact ACL injury, segmental acceleration, accelerometers, stop-jump

Unintentional musculoskeletal injury is an unfortunate consequence of participation in sports, exercise, and recreational activities and can be a significant barrier to consistent participation in a healthy and active lifestyle in civilian populations.¹ It is also a significant concern in the military as these injuries have a greater impact on health and readiness than medical complaints.² Knee injuries, for example, are a common injury in sports³⁻⁵ and in military training activities.⁶ Injuries such as anterior cruciate ligament (ACL) injuries can result in a loss of function, lead to long-term disability and early development of osteoarthritis, and prevent continued participation in sports and recreational activities.⁷⁻⁹ The identification of the cause (injury biomechanics) and risk factors for injuries is an essential component in the design of injury prevention strategies and a key step in the development of injury prevention training programs.^{10,11} The biomechanical examination of injuries is limited as it frequently involves only qualitative analysis of video or relies on the recall of injured individuals. The determination of risk factors for injury also poses methodological obstacles

as these studies require large subject numbers and, in many instances, the use of laboratory-based equipment which can limit the number of subjects tested. The development of technology that can quantify kinematic and kinetic characteristics of actual injuries which can also be employed in the field for prospective studies seems necessary to facilitate and increase our understanding of noncontact ACL injuries. Accelerometers present an opportunity to collect these in vivo data during in-game situations. They are easy to use, inexpensive, and provide quantifiable information that can be collected outside of traditional laboratory settings.

The mechanism of noncontact ACL injury has primarily been examined through the use of surveys or qualitative analysis of injury videos.¹²⁻¹⁵ Feagin qualitatively described this injury based on observations¹³ while McNair and colleagues¹⁴ interviewed individuals following their injury. Boden and colleagues¹² expanded the analysis of the injury mechanisms by utilizing both retrospective injury mechanism questionnaires and video to analyze noncontact ACL injuries. Olsen and colleagues also analyzed videotape of ACL injuries and describe the mechanism of injury.¹⁵ Interview data and qualitative video analysis of injuries are useful but they are not capable of providing accurate and detailed kinematic and kinetic data necessary for injury prevention. More recent investigations of actual game video of injuries have attempted to provide these details including Koga

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and colleagues¹⁶ who used model-based image-matching to recreate 3-dimensional kinematics and ground reaction forces during ten injuries from women's handball and basketball. Their analyses indicated that all injuries included a valgus motion immediately after initial contact with tibial rotation. Despite technological advancements, very little is known about the actual biomechanics of these injuries.

Although there are scores of descriptive comparisons between genders demonstrating biomechanical differences while performing sports tasks, relative to noncontact ACL injuries, there are only a small number of studies that have demonstrated, prospectively, biomechanical risk factors for injury.^{17,18} Historically, these studies have occurred in laboratory settings which pose some inherent limitations including the potential lack of validity of laboratory-collected biomechanical measures compared with the biomechanics that are observed in actual competition. Accordingly researchers have begun to focus on data collection either in actual competition^{19,20} or with protocols that better replicate the reactive (versus planned) nature of sport activities.^{21–25} A comparable paradigm shift has been observed relative to the examination of the forces involved in sports concussion injuries. Previously research in this area had been based on animal,^{26,27} cadaver,^{28,29} or computer modeling,^{30,31} but now researchers are utilizing accelerometers integrated into protective headwear to examine this data relative to concussions.^{32–36} The use of accelerometers in sports medicine research is not new. They have been used for the examination of overuse injuries of the lower extremity in descriptive studies.^{35,37} But, they have not been used in prospective studies, whether for overuse injuries or single-event traumatic injuries.

Accelerometers are cost effective, simple to use, and may be capable of producing meaningful data that can be collected outside of traditional laboratory settings. The overall objective of this line of research is to determine the feasibility to use an accelerometer in place of more expensive, time-consuming, and logistically demanding laboratory testing to determine, prospectively, risk factors for traumatic knee injuries. An initial step in this progression is to determine if an accelerometer mounted on the tibia correlates with laboratory-based kinetic data. Therefore, the purpose of this research study is to examine the relationship between acceleration as measured by a tibia-mounted accelerometer and proximal anterior tibia shear force and peak posterior ground reaction force. Proximal anterior tibia shear force was chosen as it is the most direct loading mechanism of the anterior cruciate ligament.^{38–41} Peak posterior ground reaction force was chosen as it is a common characteristic of different tasks that have been identified during which noncontact ACL injuries typically occur.^{12,13,42,43} Additionally, we will examine if this correlation is present as jump distance increases and if there are significant differences in the data based on jump distance. We hypothesized that there would be a correlation between acceleration, proximal anterior tibia shear force, and ground reaction forces

and that there would be a significant difference between the shortest and longest jump distances. If successful, the current study could provide evidence for the use of accelerometers in prospective studies and studies that examine in-game accelerations.

Methods

Subjects

Nineteen healthy males participated in this study (age = 25.3 ± 4.4 years, height = 175.9 ± 5.7 cm, mass = 78.2 ± 7.3 kg). All subjects were between 18 and 35 years and physically active (participated in physical activity for at least three times per week for a minimum of 30 minutes). Exclusion criteria were no leg or back injury in the previous 6 months, any history of lower extremity surgery, any injury of ACL of the knee, any disorder affecting sensation or blood flow in/to the legs, and any neurological disorder that would limit the ability to perform a jumping task. Subjects provided written informed consent in accordance with the university's Institutional Review Board before participation.

Instrumentation

Eight high-speed cameras (Vicon, Centennial, CO) collected kinematic data at 200 Hz and two force plates (Kistler Corporation, Amherst, NY) collected ground reaction forces at 1200 Hz. Kinematic and ground reaction force data were synchronized using Vicon Nexus Software (Vicon, Centennial, CO). A small wireless triaxial accelerometer (ZeroPoint Technology, Johannesburg, South Africa) with a range of ± 90 g, 0.18 g resolution, and 18 mV/g sensitivity (unamplified signal) collected tibial accelerations at 1000 Hz per axis. Acceleration data of each trial was recorded within the accelerometer and manually downloaded after each trial.

Procedures

Anthropometric measurements were recorded for each subject and included height, weight, leg length, knee width, and ankle width. Sixteen reflective markers were placed bilaterally on the subject's lower extremity using the Plug-in-Gait marker set (Vicon Motion Systems, Centennial, CO). Markers were placed on the anterior superior iliac spines, posterior superior iliac spines, lateral thighs, lateral femoral epicondyles, lateral shanks, lateral malleoli, posterior calcanei, and second metatarsal heads. A triaxial accelerometer was affixed to the flattest aspect of the medial tibia flare of the dominant leg using double-sided tape and secured with plastic stretch wrap. Axis 1 of the accelerometer was aligned along the long axis of the tibia; axis 2 was aligned in the medial-lateral direction; and axis 3 was aligned in the anterior-posterior direction (Figure 1). Leg dominance was established by asking the subject which leg they would use to kick a ball maximally. Subjects performed a series of two leg

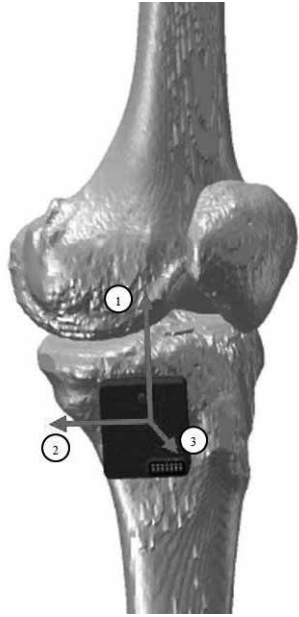


Figure 1 — Representation of triaxial accelerometer placement on the left tibia. The flattest aspect of the medial tibia flare was palpated and the accelerometer was secured using double-sided tape and plastic stretch wrap. The right-handed axes of the accelerometer are defined as shown with axis 3 coming out of the page.

stop-jump tasks with initial jump distances of 20%, 40%, 60%, and 80% of the subject's height.²⁵ Before each stop-jump, subjects performed three heel raises and were instructed to strike the ground with their heel each time. Heel raises were used to synchronize accelerometer and kinematic/kinetic data. The stop-jump task consists of an initial broad jump to a force plate, an immediate maximal vertical jump, and landing on the same force plate. The task was described and demonstrated by the researcher and any questions were answered. Subjects performed at least three practice trials before each jump distance and then three trials were collected. Time between trials was approximately 30–60 seconds. Trials were rejected if the subject did not perform the jump with two feet, did not immediately jump vertically, or did not land on the force plates.

Data Reduction

Kinematic and kinetic data were processed using the Vicon Plug-in Gait biomechanical model, based the methods of Kadaba et al⁴⁴ and Davis et al,⁴⁵ using Vicon Nexus Software (Vicon Motion Systems, Centennial, CO). Three-dimensional reflective marker trajectories were reconstructed and smoothed with a general cross-validation Woltring filter.⁴⁶ The lower extremity was defined as a seven segment rigid body model and kinematic data were calculated using Euler angle decomposition of segmental coordinate systems. Kinetic data were calculated using an inverse dynamic approach based on Newtonian

equations of motion.^{47,48} Raw ground reaction force data were low-pass filtered with a second-order zero-phase Butterworth digital filter using a cut-off frequency of 50 Hz. The cut-off frequency was selected based on a residual analysis of ground reaction force components.⁴⁸ Anthropometric and kinematic data were combined with filtered ground reaction force data to estimate proximal anterior tibia shear force.

Raw accelerometer data were filtered with a second-order zero-phase Butterworth digital filter using a cut-off frequency of 50 Hz as recommended by the manufacturer. Attachment of the accelerometer to the medial tibia flare did not allow for acceleration to be measured in the anterior-posterior plane because the accelerometer axes extend normal to its surfaces (Figure 1). Attachment to the medial flare was selected because it is a large, flat bony prominence and minimized motion artifact. Due to the variability of individual anatomy, a constant angle correction was not possible. Therefore, filtered acceleration data were analyzed from axis 2, axis 3 (Figure 1), and the resultant of these two axes.

Accelerometer data were synchronized with kinematic and kinetic data using the third ground strike during the heel raises. The time points of minimum vertical heel marker displacement and peak tibial acceleration were used as time zero for synchronization of both data sets. The first landing of the stop-jump on the force plates was used for analysis and initial contact was defined as a vertical ground reaction force greater than 5% of the subject's body weight. Peak proximal anterior tibia shear force, peak accelerations, and peak ground reaction forces after initial contact were identified using a custom Matlab (MathWorks, Natick, MA) script.

Statistical Analysis

Descriptive data including means and standard deviations were calculated for all of the variables. A Shapiro-Wilk test for normality was performed on each of the variables before performing any statistical analysis. The results of these tests demonstrated that none of the variables had a normal distribution; therefore, nonparametric tests were used for the remaining statistical analyses. A Kruskal-Wallis one-way analysis of variance test was performed for each variable across jump distance to determine if significant differences existed as jump distance increased ($P < .05$). Wilcoxon signed-rank tests were employed to examine potential differences between jump distances when the Kruskal-Wallis one-way analysis of variance test demonstrated statistical significance ($P < .05$). Spearman's rank correlation coefficients were calculated between the accelerometer data, force plate data, and proximal anterior tibia shear force to determine if significant relationships existed ($P < .05$).

Results

All variables analyzed increased as jump distance increased. Peak posterior ground reaction force, peak

acceleration axis 2, peak acceleration axis 3, and peak acceleration resultant axis 2 and 3 all were statistically significant based on the Kruskal-Wallis one-way analysis of variance test. For each of these variables there was a significant difference between the shortest and the longest jump distance (20% versus 80%). Other significant differences were also observed between various distances within each variable calculated (Table 1).

There was a significant correlation between each of the variables and jump distance as revealed by the Spearman's rank correlation coefficients calculations. The correlation coefficient calculations also revealed a significant correlation between peak posterior ground reaction force and proximal anterior tibia shear force, peak acceleration axis 1, and peak acceleration resultant axis 2 and 3. Finally, each accelerometer variable was correlated with the other two accelerometer variables (Table 2).

Discussion

The objective of the current project was to determine if acceleration measured with a tibia-mounted accelerometer correlated with laboratory based data including proximal anterior tibia shear force and posterior ground reaction force and if the accelerometer data increased as jump distance increased. We hypothesized that proximal anterior tibia shear force, accelerometer data, and peak posterior ground reaction force would all be correlated and that there would be a significance increase as jump distance increased. Our hypotheses were partially supported. A significant correlation was observed between the accelerometer data and peak posterior ground reaction force, but there was no significant correlation between proximal anterior tibia shear force and acceleration data. However, all variables significantly increased as jump distance increased and many of the multiple comparisons

Table 1 Analysis of variance across jump distance

	20% Height	40% Height	60% Height	80% Height	P
Proximal Anterior Tibia Shear Force (N/kg)	4.55 (3.17)	5.41 (3.45)	6.01 (4.37)	6.93 (4.17)	.250
Peak Posterior Ground Reaction Force (N) ^{a,b,c,d,e,f}	283.8 (118.0)	365.7 (137.5)	469.2 (155.3)	661.5 (206.7)	< .001
Peak Acceleration Axis 2 (g) ^{b,c,d,e,f}	5.29 (3.84)	6.32 (3.12)	8.12 (3.42)	10.73 (3.95)	< .001
Peak Acceleration Axis 3 (g) ^{a,b,c}	2.72 (1.15)	3.54 (1.39)	3.95 (1.18)	4.25 (1.76)	.004
Peak Acceleration Resultant Axis 2 and 3 (g) ^{b,c,d,e,f}	6.35 (3.66)	6.93 (3.00)	8.62 (3.10)	11.57 (3.84)	< .001

Note. P-values for the analysis of variance across jump distance.

^a Significant difference observed between 20% and 40%.

^b Significant difference observed between 20% and 60%.

^c Significant difference observed between 20% and 80%.

^d Significant difference observed between 40% and 60%.

^e Significant difference observed between 40% and 80%.

^f Significant difference observed between 60% and 80%.

Table 2 Pairwise correlation across all variables

	Distance		PATSF		PPGRF		PAA2		PAA3	
	Coeff.	P	Coeff.	P	Coeff.	P	Coeff.	P	Coeff.	P
Distance	NA	NA	—	—	—	—	—	—	—	—
Proximal Anterior Tibia Shear Force (PATSF)	.231	.045	NA	NA	—	—	—	—	—	—
Peak Posterior Ground Reaction Force (PPGRF)	.682	< .001	.602	< .001	NA	NA	—	—	—	—
Peak Acceleration Axis 2 (PAA2)	.541	< .001	.063	.588	.415	< .001	NA	NA	—	—
Peak Acceleration Axis 3 (PAA3)	.409	< .001	.060	.606	.222	.054	.411	< .001	NA	NA
Peak Acceleration Resultant Axis 2 and 3 (PAR)	.535	< .001	.071	.541	.357	.002	.933	< .001	.505	< .001

(between distances) were significant. Overall, the results of this study provide initial, positive support for the use of accelerometers to collect in-game acceleration data for the tibia. Although there remain logistical and methodological issues, the use of an in-game accelerometer for the tibia may be a useful data point for the prospective examination of risk factors for knee injury.

In the current study proximal anterior tibia shear force was measured through inverse dynamics, and though this measurement does not measure strain directly, previous investigators have argued that it theoretically should influence ACL loading.^{49,50} In the current study, peak posterior ground reaction force increased as expected as jump distance increased and there were significant differences in peak posterior ground reaction force between/among the different jump distances. These results indicate that as the horizontal jump distance increases the deceleration necessary to change direction increases and is similar to what has been observed in gait as gait velocity increases.⁴³ The values for proximal anterior tibia shear force also increased as jump distance increased and the correlation to jump distance was statistically significant. Our results are similar to a previous study that examined shear force and jump distance.⁵¹

All three accelerometer variables increased as jump distance increased with each demonstrating significant differences between the shortest and longest jump (20% versus 80%). There were additional significant differences between other distances measured for each of the accelerometer variables (Table 1). The accelerometer data collected in the current study compare favorably with two previous studies that have collected similar data (anterior tibial acceleration) during jumping and landing tasks.^{43,52} Comparisons to previous studies examining accelerometer data across increasing jump distance are limited as we are not aware of any studies that have examined accelerometer data compared with jump distance. Elvin et al demonstrated a correlation between peak accelerations based on a tibia-mounted accelerometer and increasing jump height.⁵³ To examine the capabilities of the accelerometer to collect relevant knee biomechanical data we examined correlations between the accelerometer and peak posterior ground reaction force and proximal anterior tibia shear force. The correlations between peak posterior ground reaction force and the accelerometer data were significant for peak acceleration axis 2 and peak acceleration resultant axis 2 and 3. Although all attempts were made to arrange for anatomical alignment, the shape of the tibia and the geometry of the accelerometer prohibited perfect alignment. Unfortunately, comparisons between our results and previous studies are very limited as we are not aware of other studies that have examined acceleration of the tibia and the two laboratory-based measures chosen in the current study (proximal anterior tibia shear force and peak posterior ground reaction force). Previous investigators have examined correlations between vertical ground reaction forces and acceleration in the vertical axis.^{53,54} Elvin et al demonstrated a correlation between

tibial acceleration (along the long axis of the tibia) and ground reaction forces.⁵⁴ The investigators used a similarly designed accelerometer, but comparisons based on the laboratory measures chosen in the current study and accelerometer are not available.

There was no correlation between the accelerometer variables and proximal anterior tibia shear force. We predicted that there would be a significant relationship between these variables based on previous work that showed a relationship between proximal anterior tibia shear force and peak posterior ground reaction force.^{49,50} Although there was a significant correlation between proximal anterior tibia shear force and peak posterior ground reaction force and a significant relationship between accelerometer data and peak posterior ground reaction force in the current study, the relationship between accelerometer data and proximal anterior tibia shear force was not significant. Potential reasons for this lack of significant differences include placement of the accelerometer, the complicated/theoretical mathematics for proximal anterior tibia shear force, and the potential that there is not a real relationship.

The objective of this research study was to determine if a tibia-mounted accelerometer could provide meaningful data relative to laboratory-based kinetic data of the lower extremity/knee and ground reaction forces. Overall, the results provide initial, positive evidence and support the hypotheses proposed, but further research is necessary to conclusively demonstrate the capability of the tibia-mounted accelerometer to collect data outside of laboratories during actual competition. There are limitations to the current study that should be addressed. The ability to measure segmental (tibia) acceleration based on an externally mounted accelerometer will be effected by movement of soft tissue relative to the segment as well as movement of the accelerometer relative to the segment. While we attempted to reduce this movement as much as possible, the issues are inherent and not completely preventable. The lack of significant increases in both variables relative to jump distance may be due to the small sample size. Additional studies are necessary to determine the reliability, validity, and capability of a tibia-mounted accelerometer to collect relevant injury biomechanical data.

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