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Title:

Biomechanical analysis of ankle ligamentous sprain injury cases from televised basketball games: understanding when, how and why ligament failure occurs

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1 Title:

2 Biomechanical analysis of ankle ligamentous sprain injury cases from
3 televised basketball games: understanding when, how and why
4 ligament failure occurs

5

6 Abstract

7 **Objectives.** Ankle sprains due to landing on an opponent's foot are common in basketball.
8 There is no analysis to date that provides a quantification of this injury mechanism. The aim
9 of this study was to quantify the kinematics of this specific injury mechanism and relate this
10 to lateral ankle ligament biomechanics.

11 **Design.** Case series.

12 **Methods.** The Model-Based Image-Matching technique was used to quantify calcaneo-
13 fibular-talar kinematics during four ankle inversion sprain injury incidents in televised NBA
14 basketball games. The four incidents follow the same injury pattern in which the players of
15 interest step onto an opponent's foot with significant inversion and a diagnosed ankle injury.
16 A geometric analysis was performed to calculate the *in vivo* ligament strains and strain rates
17 for the anterior talofibular ligament (ATFL) and the calcaneofibular ligament (CFL).

18 **Results.** Despite the controlled selection of cases, the results show that there are two
19 distinct injury mechanisms: sudden inversion and internal rotation with low levels of
20 plantarflexion; and a similar mechanism without internal rotation. The first of these
21 mechanisms results in high ATFL and CFL strains, whereas the second of these strains the
22 CFL in isolation.

23 **Conclusions.** The injury mechanism combined with measures of the ligament injury in terms
24 of percentage of strain to failure correlate directly with the severity of the injury quantified by
25 return-to-sport. The opportunity to control excessive internal rotation through proprioceptive
26 training and/or prophylactic footwear or bracing could be utilised to reduce the severity of
27 common ankle injuries in basketball.

28 **Keywords:** injury mechanism; ankle; return-to-sport; inversion; internal rotation

29

30 Introduction

31 The ankle is the most widely injured part of the body during sport, accounting for 10% to
32 30% of all sport-related injuries^{1,2,3,4} and ankle injuries sustained by athletes create an
33 annual healthcare burden of over \$4 billion in the U.S alone.⁵ The most common ankle
34 injuries involve the lateral ligaments.² Lateral ligament injuries in basketball players can
35 cause significant reduction in playing ability⁶ that may result in match defeats and economic
36 loss to the individual and the team. Understanding the injury mechanism in detail would
37 allow the development of new preventative strategies and the design of protective equipment
38 for basketball players.⁷

39 The Model-based image-matching (MBIM) technique utilises uncalibrated video sequences
40 to reconstruct three-dimensional human motion patterns and estimate temporal joint angle
41 histories, velocities and accelerations.⁸ This method has been applied in two different
42 studies, which aimed to explore the biomechanics of five actual ankle injuries from televised
43 tennis competitions⁷ and another two injuries during the 2008 Beijing Olympics.⁹ Both
44 studies reported the peak values of ankle joint internal rotation and inversion, such as the
45 values of inversion velocity. The results indicated that ankle ligament injuries resulted from
46 the combination of internal rotation and sudden inversion of the ankle joint, while
47 plantarflexion was absent.^{7,9,10} While kinematics are very important for understanding the
48 injury mechanism of an injury, there has been no similar analysis to date that quantifies
49 ligament loading patterns during injury in a quantitative manner, including, for example,
50 ligament strain or strain rate.

51 Therefore, the aim of this study was to quantify the detailed injury mechanism of the ankle
52 during real ankle injury cases by quantifying ankle kinematics, *in vivo* ligament strains, strain
53 rates and loading.

54 Methods

55 A single common injury mechanism was selected in which a large unwanted ankle inversion
56 secondary to inadvertently stepping onto an opponent's foot during an elite level basketball
57 game was experienced. The inclusion criteria were: conforming to the selected injury
58 mechanism; the player was unable to continue playing after the injury or had problems
59 playing (following the approach taken by Fong and Wei¹⁰); the injury was reported as an
60 ankle sprain injury in the post-match report; two camera views of the incident were available
61 (showing the shank and foot segment clearly and showing an extreme inversion sprain
62 motion) with a video resolution of at least 640x360 pixels with a frame rate of at least 25 Hz
63 (the minimum frame rate deemed appropriate in prior work⁷), and the basketball game was
64 of an elite level. Four cases that occurred during televised NBA basketball games were
65 available.

66 In order to present and compare the results for four different cases, which have different time
67 lengths, time-normalisation was employed. The start point was defined as the time (frame) of
68 first contact between the player of interest's injured foot and the opponent's foot. The end
69 point was defined as the time (frame) when the player of interest's injured foot does not have
70 any contact with the opponent's foot or the ground. The dependent variables were then
71 normalised to the percentage of the injury incident.

72 The videos were trimmed and edited in order to create uncompressed AVI image sequences
73 for each camera view with Adobe Premiere Pro software (version CS5.5, Adobe Systems
74 Inc., San Jose, CA, USA). Then, AVI image sequences were merged and rendered into a
75 synchronised video sequence by Adobe After Effects (version CS5.5, Adobe Systems Inc.,
76 San Jose, CA, USA).

77 An anthropometric data figure was used in order to calculate the lengths of each lower limb
78 segment (foot length and breadth, shin length and thigh length) relative to the total height of
79 each basketball player (source: www.nba.com) and build a skeleton model for the matching

80 process. The skeleton model from Zygote Media Group Inc. was used. The skeletal
81 structures and court dimensions were matched to the video images using Poser 4 and Poser
82 Pro Pack (Curious Labs, Inc., Santa Cruz, CA, USA) software. The dimensions of the
83 basketball court in each case were obtained from the National Basketball Association to
84 construct a virtual environment.

85 The virtual environment was manually matched to the image background for each frame in
86 every camera view, using a key frame and spline interpolation technique by adjusting the
87 camera calibration parameters: position, orientation and focal length. The skeleton model
88 used for the skeleton matching of the lower limb consisted of four rigid segments: foot,
89 tibia/fibula, thigh and pelvis. The complete matching process is fully described by Krosshaug
90 and Bahr.⁸ The adjustment of Mok et al.¹¹ was used to define the ankle joint centre, following
91 the International Society of Biomechanics (ISB) recommendation.¹² Finally, frame by frame
92 adjustments were made to ensure smooth motion of the cameras and the skeleton for each
93 case (Figure 1).

94 <FIGURE 1>

95 Ankle joint kinematics data were calculated from the skeletal matching data. Poser 4 and
96 Poser Pro Pack were used to export the ankle joint angle histories that were subsequently
97 imported into a custom-written Matlab scripts to compute joint angles according to a Joint
98 Coordinate System method¹³, following the ISB recommendations¹².

99 Data were filtered and interpolated by Woltring's generalised cross-validation spline package
100 with 15 Hz cut-off frequency. The kinematic data were then used to quantify lateral ankle
101 ligament length changes to then calculate the ligament strains and strain rates to infer injury
102 data. The two key ligaments that are loaded during the proscribed injury mechanism were
103 identified, these are the anterior talofibular ligament (ATFL) and the calcaneofibular ligament
104 (CFL). Within the virtual environment in Poser 4, the anatomical insertion points of the two
105 ligaments were identified and marked with spherical features (Figure 2). The insertion

106 positions were located for each time frame. The unloaded lengths of the ligaments (L_0) were
107 calculated with the skeleton orientated in the standing position and then ligament lengths
108 were calculated as the linear distance between insertion points for each time step, following
109 the 'minimal recruitment length' approach of Blankevoort et al.¹⁴

110 <FIGURE 2>

111 Engineering strain at each point was calculated as the ratio of length change over original
112 length

113

114 Engineering strain rate was calculated as follows:

115

116 Maximum Load, stiffness, deflection to failure and strain to failure across the strain rates
117 experienced were calculated for both ligaments using scaled data from the literature.
118 Attarian et al¹⁵ found that the ATFL and CFL had stiffnesses of 272±46 N/cm and 549±88
119 N/cm, respectively from a mean donor age of 57.9 years, loaded at strain rates of 96/s and
120 61/s. Recent work has shown that there is no strain rate effect on maximum stress and
121 ultimate load for ligaments when loaded above 1/s.¹⁶ and the expected strain rates in the
122 four cases are above 1/s, therefore no strain rate scaling is required for the above data.

123 The ultimate load of ligaments decreases with age according to an exponential decay¹⁷:

124 . This was use to scale the properties from Attarian et al¹⁵ to the mean age
125 of the four cases in this study (29 years), with $\lambda=0.2$ and $t=29$.

126 Woo et al¹⁷ found that stiffness decreased by 16% from a young age group to an older age
127 group, therefore the stiffness data, deflection to failure and strain to failure of the ATFL and
128 the CFL from the Attarian et al¹⁵ data were scaled for the younger group (Table 1).

129

<TABLE 1 HERE>

130 All four injuries are described below.

131 Case 1: The injured player suffered from a left ankle sprain in a game for the NBA's regular
132 season. His team announced that he had suffered from a sprain and a bone bruise and was
133 ruled out for two weeks.

134 Case 2: The injured player suffered from a right ankle injury in the first half in Game 3 of the
135 Eastern Conference NBA Quarterfinals. He returned later on in that game in obvious
136 discomfort and played the following three games on playing time restriction with a
137 significantly reduced performance. These were the last games in the season and further
138 information on the injured player's rehabilitation was not available.

139 Case 3: The injured player sprained his right ankle in the first quarter in this year's Game 4
140 of the Western Conference NBA Finals. He tried to play on, however, in obvious pain,
141 missed the rest of the game. He played the following game without time restriction.

142 Case 4: The injured player sprained his left ankle in Game 3 of the Eastern Conference NBA
143 Quarterfinals. He was ruled out of playing for at least 3 months. Due to usual restrictions on
144 medical data from elite athletes, no medical imaging and orthopaedic reports were available.

145 Results

146 Case data and all quantitative results are presented in Table 2.

147

<TABLE 2 HERE>

148 Ankle kinematics and ligament strains are presented in Figure 3, demonstrating that all
149 cases exhibit a high level of inversion ($>70^\circ$) with no plantarflexion. Case 1 has very little
150 internal rotation and all other cases exhibited large internal rotation ($>25^\circ$). All cases
151 demonstrate similar maximum strains for the CFL, with Case 1 having low strains for the
152 ATFL when compared to the other three cases.

153

<FIGURE 3>

154 The case analysis below proposes the injury magnitude through an analysis of maximum
155 strain to the ATFL and CFL. This is recorded as “injury assessment” in Table 2.

156 Case 1: The maximum ATFL strain was 18%, which is significantly below the strain to
157 failure. The maximum CFL strain was 61%, which exceeds the strain to failure, suggesting a
158 complete rupture of the CFL. The player was ruled out of sport for two weeks.

159 Case 2: The maximum ATFL strain was 71%, which is approximate at the strain to failure
160 (67%). The maximum CFL strain was 47%, which is equal to the approximate strain to
161 failure. The most probably outcome, therefore, was that the CFL and ATFL each sustained
162 minor sprains. The player continued to play below his normal standard.

163 Case 3: The maximum ATFL strain was 47%, which is below the strain to failure. The
164 maximum CFL strain was 53%, above the strain to failure. The most likely outcome was that
165 the ATFL was kept intact and the CFL was moderately sprained. The player returned to
166 action after only two days.

167 Case 4: The maximum ATFL strain value was 73%, which is just greater than the strain to
168 failure (67%). The maximum CFL strain was 49%, also slightly over the strain to failure
169 (47%), suggesting that both ligaments sustained moderate sprains, similar to Case 2, at a
170 slightly more severe level. The player was ruled out of sport for three months.

171 Discussion

172 All cases analysed here follow a similar pattern. The main factor causing the injury is that the
173 injured player steps onto an opponent’s foot (abnormal landing) to create an ankle injury.
174 The consistent features in these injury patterns are a sudden inversion and low values (10-
175 35°) of plantarflexion. The lack of plantarflexion indicates that the subtalar joint had little
176 involvement in the injury mechanism. There was great variability in peak internal rotations (3-

177 47°) across the four cases. These results are similar to those in the literature ^{7,9,18}, however,
178 very low internal rotation has not been shown previously.

179 Basketball is a sport that requires frequent jumps and landings, cutting manoeuvres and
180 contact with other players and thus observing different injury mechanisms is expected.
181 However, the short injury duration and high inversion velocities in all cases indicate that the
182 preventative measures should focus on resisting the inversion torque at the ankle joint for a
183 very short period of time. Proposed mechanisms to achieve this include neuromuscular
184 training on correct foot landing¹⁹, shoe design such as higher ankle support, and myoelectric
185 anti-sprain stimulation²⁰.

186 This study has a number of key limitations, in particular, we were limited by the number of
187 cases. The minimum frame rate in this study was 25 Hz⁷, and, although this has been
188 previously deemed appropriate for such analyses, a higher frame rate and higher resolution
189 of the images would also greater resolution and accuracy for the measures of ankle
190 kinematics and ligament strains. The manual skeletal scaling and matching process is
191 subject to user experience and this was conducted by the most experienced member of the
192 team. In addition, the estimation of the rehabilitation time period of each player was based
193 on injury reports from online sources and detailed medical information was not available.
194 The geometric analysis presumes a straight line between ligament insertions without
195 accounting for any possible wrapping. In these cases this wrapping is expected to be
196 negligible.

197 Conclusion

198 A quantitative analysis was performed to identify and calculate ankle joint kinematics and
199 ligament strains in a specific injury mechanism in elite level basketball. We noted two distinct
200 injury mechanisms in our case series: sudden inversion and internal rotation with low levels
201 of plantarflexion; and a similar mechanism without internal rotation. The hypothesis that the
202 first of these mechanisms results in ATFL and CFL sprains or ruptures, whereas the second

203 of these damages the CFL in isolation. A link between return-to-sport and ligament strain
204 parameters may be inferred from this work, but this cannot be proven without an appropriate
205 medical history.

206 Practical Implications

- 207 • The specific injury mechanism of landing on an opponent's foot can produce isolated
208 rupture of the calcaneofibular ligament of the ankle or a combined rupture of this
209 ligament and the anterior talofibular ligament
- 210 • This injury mechanism consists of excessive internal rotation and inversion.
- 211 • Reducing internal rotation alone through proprioceptive training and/or prophylactic
212 footwear or bracing will protect the anterior talofibular ligament thus facilitating a
213 faster return to sport.

214 Acknowledgments

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216

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Table Legends

Table 1: Derived biomechanical data of the anterior talofibular ligament (ATFL) and the calcaneofibular ligament (CFL) for four basketball players with mean age of 29 years old.

Table 2: Case data and quantitative results for the 4 different injury cases.

Table 1

	ATFL	CFL
Maximum Load (N)	245 ± 40	610 ± 97
Stiffness (N/cm)	368 ± 62	742 ± 118
Deflection to Failure (cm)	0.67	0.82
Strain to Failure (%)	64	47

Table 2

	Case 1	Case 2	Case 3	Case 4
Minimum video resolution (pixels)	1280x720	640x360	1280x720	640x360
Frame rate (Hz)	30	30	30	29.9
Player height (m)	2.11	2.03	1.91	2.11
Player mass (kg)	111.1	102.1	94.3	105.2
Player age (years)	33	32	24	27
Injury severity (days of absence)	14	0 (reduced performance)	2	90
Peak Inversion (°)	92.7	77.4	96.6	107.5
Time to Peak Inversion (sec)	0.17	0.13	0.23	0.23
Peak Internal Rotation (°)	3.4	38.2	28.0	46.6
Time to Peak Internal Rotation (sec)	0.1	0.13	0.17	0.4
Peak Plantarflexion (°)	3.2	26.4	12	53.9
Time to Peak Plantarflexion (sec)	0.13	0.1	0.2	0.47
Maximum ATFL strain (%)	17.6	70.9	47.1	72.5
Time to maximum ATFL strain (sec)	0.13	0.13	0.23	0.3
Maximum CFL strain (%)	60.8	46.5	53.0	48.7
Time to maximum CFL strain (sec)	0.17	0.13	0.23	0.23
Mean Value of ATFL Strain Rate (/s)	1.3	3	1.8	2
Mean Value of CFL Strain Rate (/s)	2.6	2.4	2	1.6
ATFL injury assessment	No	Minor Injury	No	Moderate Injury
CFL injury assessment	Complete Rupture	Minor Injury	Moderate Injury	Moderate Injury

Figure Legends

Figure 1: Virtual environment (basketball court lines and basket were created manually) and skeleton matching (Case 4).

Figure 2: Matching procedure for calculating the lengths of the two key ligaments (Case 1).

Figure 3: Ankle kinematics and ligament strain for four cases of ankle inversion injury

Figure 1



Figure 2

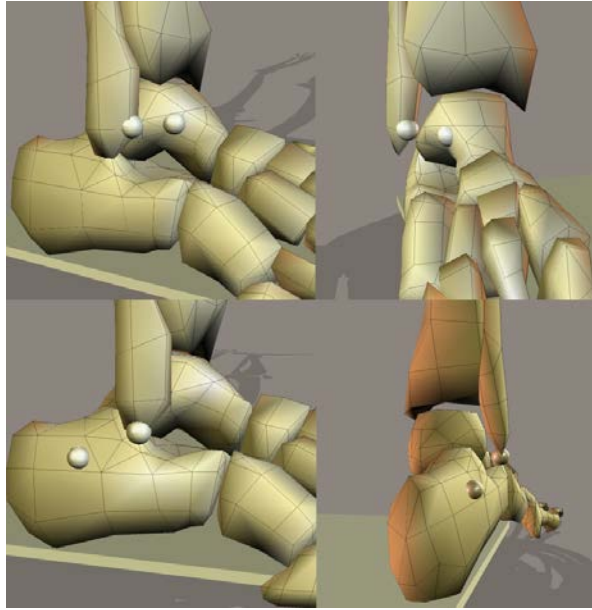


Figure 3

