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

PLEASE CITE THE PUBLISHED VERSION

<http://dx.doi.org/10.1016/j.jsams.2017.05.006>

PUBLISHER

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VERSION

AM (Accepted Manuscript)

PUBLISHER STATEMENT

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Panagiotakis, Emmanouil, Kam-Ming Mok, Daniel Tik-Pui Fong, and Anthony M.J. Bull. 2019. "Biomechanical Analysis of Ankle Ligamentous Sprain Injury Cases from Televised Basketball Games: Understanding When, How and Why Ligament Failure Occurs". figshare. <https://hdl.handle.net/2134/25252>.

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<sup>1,2,3,4</sup> and ankle injuries sustained by athletes create an  
33 annual healthcare burden of over \$4 billion in the U.S alone.<sup>5</sup> The most common ankle  
34 injuries involve the lateral ligaments.<sup>2</sup> Lateral ligament injuries in basketball players can  
35 cause significant reduction in playing ability<sup>6</sup> 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.<sup>7</sup>

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.<sup>8</sup> 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 competitions<sup>7</sup> and another two injuries during the 2008 Beijing Olympics.<sup>9</sup> 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.<sup>7,9,10</sup> 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 Wei<sup>10</sup>); 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 work<sup>7</sup>), 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](http://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.<sup>8</sup> The adjustment of Mok et al.<sup>11</sup> was used to define the ankle joint centre, following  
91 the International Society of Biomechanics (ISB) recommendation.<sup>12</sup> 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 method<sup>13</sup>, following the ISB recommendations<sup>12</sup>.

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.<sup>14</sup>

110 <FIGURE 2>

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

113 
$$\text{Strain } (\varepsilon) = \frac{\Delta L}{L_0}$$

114 Engineering strain rate was calculated as follows:

115 
$$\text{Strain Rate } (\varepsilon(t)) = \frac{d\varepsilon}{dt}$$

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 al<sup>15</sup> 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.<sup>16</sup> 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 decay<sup>17</sup>:  
124  $N = N_0 \times e^{-\lambda t}$ . This was used to scale the properties from Attarian et al<sup>15</sup> to the mean age  
125 of the four cases in this study (29 years), with  $\lambda=0.2$  and  $t=29$ .

126 Woo et al<sup>17</sup> 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 al<sup>15</sup> 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<sup>7,9,18</sup>, 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 landing<sup>19</sup>, shoe design such as higher ankle support, and myoelectric  
185 anti-sprain stimulation<sup>20</sup>.

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 Hz<sup>7</sup>, 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

215 No financial support was provided for this study.

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

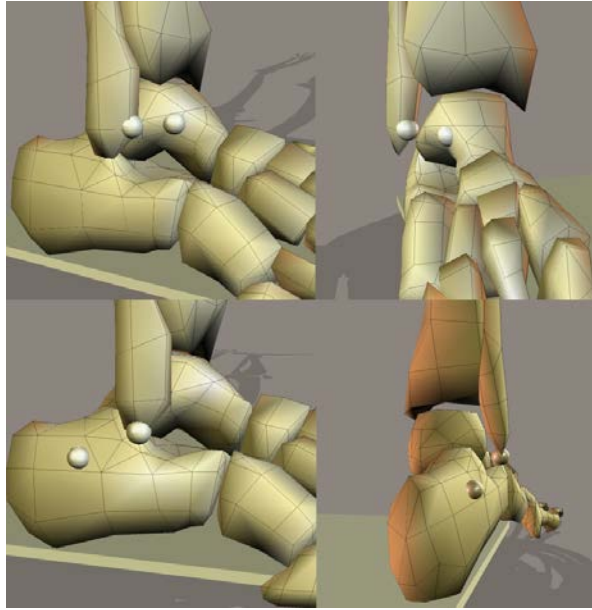


Figure 3

