

1 **Title:** Kinematics analysis of ankle inversion ligamentous sprain injuries in sports -

2 five cases from televised tennis competitions

3

4 **What is known about the subject**

5 Video analysis of real injury incidents gives valuable information for the

6 understanding of injury mechanism. For ankle inversion sprain injury, 4 quantitative

7 case reports have been reported from 3 recent articles,^{10,12,17} suggesting the

8 importance of ankle joint internal rotation as one of the causes to incite an ankle

9 inversion injury. However the available data is still too little to draw a more

10 representative conclusion.

11 **Adds to existing knowledge**

12 This paper reveals the kinematics of ankle inversion ligamentous sprain of five cases

13 from televised tennis competitions. The results are in agreement with previous reports,

14 suggesting that internal rotation is a key component of the injury mechanism of lateral

15 ankle joint sprain. It also suggests that an inverted ankle orientation at landing could

16 be an inciting event.

17

18 **INTRODUCTION**

19 Ankle ligamentous sprain is the most common injury in sports, with the majority

20 having an inversion or supination mechanism presented clinically and qualitatively.⁹
21 Understanding the injury mechanism, preferably with biomechanics quantities, is a
22 key component required for the development of injury prevention protocols and the
23 design of protective equipment.² With the advance of sport biomechanics technique,
24 numerous approaches have emerged for the quantitative understanding of injury
25 mechanism.¹³ Among different methods, the most direct way is to investigate real
26 injury incidents, however, it is unethical and practically impossible to perform
27 experiments where test subjects are purposefully injured. In rare cases, accidents
28 occurred unexpectedly in a biomechanics laboratory with calibrated motion analysis
29 equipment. There were two recent such reports on ankle inversion sprain injury with
30 reported kinematics data.^{10,12} In each study, the subject participated in a biomechanics
31 test with a sideward cutting motion, and accidentally sustained an inversion ankle
32 sprain injury.

33

34 There are far more real injury incidents captured unintentionally on televised sports
35 events than in biomechanics laboratory, however, the environments of the sports
36 venues are less or even not calibrated. The first ever real injury analysis during a
37 sports event was published in 1977, which reported a human patellar tendon rupture
38 captured unintentionally during a weight lifting competition.²⁵ There was a calibrated

39 camera capturing the sagittal plane motion of the athlete at 50 frames per second, and
40 together with another age-, body mass- and height-matched experienced weight-lifter
41 performing the motion again in a laboratory environment, the resultant knee joint
42 moment at the time of tendon rupture was determined mathematically. The
43 well-aligned camera and the consistent weight-lifting performance as demonstrated by
44 another experienced weight-lifter made the analysis possible. In many other occasions,
45 injury motions were captured during unanticipated moves and under un-calibrated
46 environment with panning cameras. To cope with this, Krosshaug and Bahr¹⁴
47 developed a model-based image-matching (MBIM) motion analysis technique to
48 analyse three-dimensional human motion from un-calibrated video sequences, and
49 successfully utilized the method to analyse knee joint ligamentous injury in sports.¹⁵

50

51 The technique was recently further developed to investigate ankle joint motion,¹⁶ and
52 was employed to investigate two cases during the 2008 Beijing Olympics.¹⁷ This
53 study presented five cases in tennis and a comparison with three previous studies for a
54 better understanding of the mechanism of ankle ligamentous sprain injury.

55

56 **METHOD**

57 An online video search was performed. To be included in the analysis, a video must

58 have at least 2 camera views showing the shank, the ankle joint and the foot segment
59 during the injury motion. An injury motion was defined as when the athlete (1)
60 performed an unwanted excessive ankle inversion during a landing and sideward
61 cutting motion with the foot segment rolling over the lateral edge of the foot, (2)
62 needed to withdraw from the game or to continue after a brief rest with treatment to
63 the ankle joint, (3) was reported to have sustained the ankle sprain injury from the
64 post-match report. Five injury cases in various televised tennis competitions were
65 presented in this study (Table 1). Invitation letters were sent to the address of each
66 injured athlete's home, tennis club or association, and fans club to seek for informed
67 consent, medical diagnosis and other information of the injury incident, but none of
68 the five injured athletes replied. The university ethics committee approved the study,
69 and the identities of the athletes have to be hidden for the sake of patient privacy

70

71 **Model-Based Image-Matching motion analysis**

72 Details of the MBIM motion analysis were reported previously.¹⁶ The videos were
73 transformed into uncompressed AVI image sequence with Premiere Pro, de-interlaced
74 with Photoshop, and then synchronized and rendered into 1Hz video sequences by
75 After-Effects (Adobe CS4, Adobe Systems Inc, San Jose, California, US). The video
76 sequences were then matched by 3D animation software (Poser 4 & Poser Pro Pack,

77 Curious Labs Inc, Santa Cruz, California, US). The dimensions of the tennis court in
78 each case were obtained from International Tennis Federation to build a virtual
79 environment. A skeleton model (Zygote Media Group Inc, Provo, Utah, US) scaled to
80 the injured athlete's height was used for the skeleton matching, firstly on the shank
81 segment and then the foot and toe segments. The matching of the virtual tennis court
82 environment and the skeleton model was done simultaneously frame by frame. The
83 matched video sequence and the skeleton model are available online at
84 <http://ajs.sagepub.com/supplemental/>.

85

86 The foot strike was determined visually from the video sequence. The profile of the
87 ankle joint orientation was then read into a self-compiled script (Matlab, MathWords
88 Inc, Natick, Massachusetts, US) for calculating the joint kinematics by the joint
89 coordinate system method.¹¹ The ankle joint kinematics of each case was presented at
90 video frame frequency until at most 0.50 second after foot strike if data is available,
91 and was presented individually but not after averaging all five cases as we expected
92 great variations and perhaps different trends across the different cases. The data were
93 presented in accordance to the recommendation of the International Society of
94 Biomechanics,²⁴ and were filtered and interpolated by Woltring's generalized
95 cross-validation spline package with 15Hz cut-off frequency.²³

96

97 **RESULTS**

98 Figure 1 showed the moment with the greatest ankle inversion in each case from one
99 view, and the matched skeleton model in 3 planes for visual comparison. Figure 2
100 showed the profile of ankle kinematics, while Table 2 showed the peak angle, velocity,
101 time to peak angle, and the comparison with the cases reported in three previous
102 studies. Great variations of the peak inversion and peak internal rotation were
103 observed in the 5 injury cases, which reached 48-126 degrees and 35-99 degrees
104 respectively. Nevertheless, there was still a trend of sudden inversion and internal
105 rotation at the ankle joint, but a fluctuation around the neutral position for
106 plantarflexion and dorsiflexion within the first 0.50 second after foot strike. The peak
107 inversion velocity of the 5 cases in this study ranged from 509 to 1488 deg/s, which
108 were comparable to the data reported in the previous studies which ranged from 632
109 to 1752 deg/s.^{10,12,17}

110

111 **DISCUSSION**

112 The result of this study is in agreement with previous studies which suggested that
113 plantarflexion is absent but internal rotation is present at the time of peak ankle

114 inversion during the injuring motion.^{10,12,17} Case 2 showed the same peak inversion
115 but a smaller peak inversion velocity to the case presented by Fong and colleagues,¹⁰
116 but a larger peak internal rotation and a larger internal rotation at the time of peak
117 inversion, which were about 25-26 degrees respectively. The case presented by
118 Kristianslund and colleagues¹² also showed a small inversion of about 35 degrees, but
119 a larger internal rotation of 55 degrees. These findings suggested that the previously
120 suggested clinical qualitative injury mechanism, which was supination, or a talocrural
121 joint plantarflexion with the sub-talar joint adducting and inverting²², may not be the
122 only possible mechanism to cause an ankle inversion sprain injury. When one sustains
123 an ankle sprain injury whilst landing from a jump, the ankle joint is likely to be
124 plantarflexed prior to landing, and therefore a combined inversion plus plantarflexion
125 might be the injury mechanism. In tennis, there are more horizontal sideward
126 movements in medial and lateral directions, but fewer vertical jump-landing motions
127 which may happen more frequently in basketball and volleyball. Therefore, in tennis,
128 instead of plantarflexion, internal rotation could also be one of the causes of ankle
129 inversion sprain injury, especially for a planted foot on the sports ground which could
130 not further plantarflexed into the ground. Further similar studies should be conducted
131 in other sports as the nature of different sport event would not be the same.

132

133 There were cadaveric studies in the literature suggesting the effect of different ankle
134 joint orientations and loads on the anterior talofibular ligament. In 1988, Renstrom
135 and coworkers²⁰ found that when the ankle joint changed from 10 degree dorsiflexion
136 to 40 degree plantarflexion, the strain of the anterior talofibular ligament increased by
137 3.3%. There was no increase during internal rotation, but a 1.9% decrease in external
138 rotation. In 1998, Bahr and coworkers³ found the largest increase in force in anterior
139 talifibular ligament when the ankle joint was supinated and plantarflexed with a 76N
140 compressive load. Based on the results, they suggested that the anterior talofibular
141 ligament is a primary restraint in inversion, where injuries typically occur in
142 combined plantarflexion, supination and internal rotation. In a recent study, Ringleb
143 and coworkers²¹ reported that when the anterior talofibular ligament was sectioned,
144 the maximum ankle joint motion has increased in inversion (6.9 to 11.2 degrees),
145 internal rotation (6.1 to 14.9 degrees), internal rotation component during supination
146 (14.8 to 23.0 degrees), but not in inversion component during supination. The findings
147 from these studies suggested that the anterior talofibular ligament would tighten in
148 plantarflexion, as well as internal rotation. Therefore, excessive and explosive
149 plantarflexion or internal rotation on an inverted ankle joint would cause stress and
150 may rupture the anterior talofibular ligament.

151

152 In all cases but Case 5, the peak inversion was achieved explosively in a very short
153 time after foot strike (0.09-0.17s). Another similarity was that they all presented with
154 a slightly inverted ankle joint (10-24 degrees) at the time of foot strike, which is a
155 vulnerable joint orientation to cause the injury.¹ There were also numerous studies in
156 subjects with chronic ankle instability showing an increased ankle inversion as the
157 cause of the sprain injury.^{4-8,18} Another recent study also suggested that patients with
158 chronic ankle instability demonstrated a laterally shifted centre of pressure during
159 running.¹⁹ We believe that such a shifted centre of pressure would indicate a slightly
160 inverted ankle joint, which could have incited the ankle sprain injuries in this study.
161 For Case 5, the ankle joint was at a neutral orientation at the foot strike, however, it
162 ultimately increased gradually to around 15 degrees after 0.1s, to 50 degrees after 0.3s,
163 and as much as 130 degrees after 0.5s. We believe that the patient had undergone a
164 pre-injury phase during this 0.1s as compared to the case presented by Fong and
165 colleagues¹⁰. The progression of the plantar pressure might have gone wrong,
166 probably by shifting to the lateral side, thus causing the foot to roll over the lateral
167 edge and incited the injury.

168

169 There is also a limitation as we could not tell if the excessive inversion and internal
170 rotation were the cause or the consequence of the ankle sprain injury. Therefore, it

171 may be more sensible to interpret the velocity of the motion instead of just the range
172 of the motion. One may also suggest that the velocity of the motion at the initial
173 contact would be the critical parameter. However, in an earlier case report¹⁰, a
174 biphasic pattern was observed, with a pre-injury phase happening from 0.06 to 0.11
175 seconds and the injury phase from 0.11 seconds onward after the initial contact, as
176 suggested after observing the deviation of plantar pressure excursion path. Since we
177 expect that there would often be a great variation among different injury incidents, we
178 presented the profile of each single case but not the overall mean profile among the
179 five cases. The peak inversion velocities varied among a wide range, but they were in
180 general higher than the 2 accidental injury cases in laboratory environment (632 and
181 559 deg/s),^{10,12} and lower than the 2 cases happened during real competitions (1752
182 and 1397 deg/s).¹⁷

183

184 **CONCLUSION**

185 The five ankle inversion ligamentous sprain cases in this study suggested that large
186 and sudden inversion and internal rotation but not plantarflexion had happened.
187 Internal rotation could be one of the causes of ankle inversion sprain injury. The
188 slightly inverted ankle orientation at landing could be an inciting event. We
189 recommend tennis players who do lots of sideward cutting motions to try their best to

190 land with a neutral ankle orientation, and to keep their centre of plantar pressure from
191 shifting to the lateral aspect, in order to prevent the foot from rolling over the edge to
192 cause an ankle inversion sprain injury.

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194 **References:**

195 1. Andersen TE, Floerenes TW, Arnason A, et al. Video analysis of the mechanisms
196 for ankle injuries in football. *American Journal of Sports Medicine*.
197 2004;32:S69-79.

198 2. Bahr R, Krosshaug T. Understanding injury mechanisms: a key component of
199 preventing injuries in sports. *British Journal of Sports Medicine*.
200 2005;39:324-329.

201 3. Bahr R, Pena F, Shina J, Lew WD, Engebretsen L. Ligament force and joint
202 motion in the intact ankle: a cadaveric study. *Knee Surgery Sports Traumatology*
203 *Arthroscopy*. 1998;6:115-121.

204 4. Brown C. Foot clearance in walking and running in individuals with ankle
205 instability. *American Journal of Sports Medicine*. 2011;39(8):1769-1776.

206 5. Brown C, Padua D, Marshall SW, et al. Individuals with mechanical ankle
207 instability exhibit different motion patterns than those with functional ankle
208 instability and ankle sprain copers. *Clinical Biomechanics*. 2008;23(6):822-831.

209 6. Delahunt E, Monaghan K, Caulfield B. Altered neuromuscular control and ankle
210 joint kinematics during walking in subjects with functional instability of the
211 ankle joint. *American Journal of Sports Medicine*. 2006;34(12):1970-1976.

- 212 7. Delahunt E, Monaghan K, Caulfield B. Ankle function during hopping in
213 subjects with functional instability of the ankle joint. *Scandinavian Journal of*
214 *Medicine and Science in Sports*. 2007;17(6):641-648.
- 215 8. Delahunt E, Monaghan K, Caulfield B. Changes in lower limb kinematics,
216 kinetics, and muscle activity in subjects with functional instability of the ankle
217 joint during a single leg drop jump. *Journal of Orthopaedic Research*.
218 2006;24(10):1991-2000.
- 219 9. Fong DTP, Hong Y, Chan LK, et al. A systematic review on ankle injury and
220 ankle sprain in sports. *Sports Medicine*. 2007;37:73-94.
- 221 10. Fong DTP, Hong Y, Shima Y, et al. Biomechanics of supination ankle sprain - a
222 case report of an accidental injury event in laboratory. *American Journal of*
223 *Sports Medicine*. 2009;37:822-827.
- 224 11. Grood ES, Suntay WJ. A joint coordinate system for the clinical description of
225 three-dimensional motions: application to the knee. *Journal of Biomechanical*
226 *Engineering*. 1983;105:136-144.
- 227 12. Kristianslund E, Bahr R, Krosshaug T. Kinematics and kinetics of an accidental
228 lateral ankle sprain. *Journal of Biomechanics*. 2011;44:2576-2578.
- 229 13. Krosshaug T, Andersen TE, Olsen OEO, et al. Research approaches to describe
230 the mechanisms of injuries in sport: limitations and possibilities. *British Journal*
231 *of Sports Medicine*. 2005;39:330-339.
- 232 14. Krosshaug T, Bahr R. A model-based image-matching technique for
233 three-dimensional reconstruction of human motion from uncalibrated video
234 sequences. *Journal of Biomechanics*. 2005;38:919-929.

- 235 15. Krosshaug T, Nakamae A, Boden BP, et al. Mechanisms of anterior cruciate
236 ligament injury in basketball: video analysis of 39 cases. *American Journal of*
237 *Sports Medicine*. 2007;35:359-367.
- 238 16. Mok KM, Fong DTP, Krosshaug T, et al. An ankle joint model-based
239 image-matching motion analysis technique. *Gait and Posture*. 2011;34:71-75.
- 240 17. Mok KM, Fong DTP, Krosshaug T, et al. Kinematics analysis of ankle inversion
241 ligamentous sprain injuries in sports: 2 cases during the 2008 Beijing Olympics.
242 *American Journal of Sports Medicine*. 2011;39:1548-1552.
- 243 18. Monaghan K, Delahunt E, Caulfield B. Ankle function during gait in patients
244 with chronic ankle instability compared to controls. *Clinical*
245 *Biomechanics*.2006;21(2):168-174.
- 246 19. Morrison KE, Hudson DJ, Davis IS, et al. Plantar pressure during running in
247 subjects with chronic ankle instability. *Foot and Ankle International*.
248 2010;31:994-1000.
- 249 20. Renstrom P, Wertz M, Incavo S, Pope M, Ostgaard H C, Arms S, Haugh L. Strain
250 in the lateral ligaments of the ankle. *Foot and Ankle*. 1988;9:59-63.
- 251 21. Ringleb SI, Dhakal A, Anderson CD, Bawab S, Paranjape R. Effects of lateral
252 ligament sectioning on the stability of the ankle and subtalar joint. *Journal of*
253 *Orthopaedic Research*. 2011;29:1459-1464.
- 254 22. Vitale TD, Fallat LM. Lateral ankle sprains: evaluation and treatment. *Journal of*
255 *Foot Surgery*. 1988;27:248-258.
- 256 23. Woltring HJ. A Fortran package for generalized, cross-validation spline
257 smoothing and differentiation. *Advances in Engineering Software*.

258 1986;8:104-113.

259 24. Wu G, Siegler S, Allard P, et al. ISB recommendation on definitions of joint
260 coordinate system of various joints for the reporting of human joint motion, part
261 I: ankle, hip, and spine. *Journal of Biomechanics*. 2002;35:543-548.

262 25. Zernicke RF, Garhammer J, Jobe FW. Human patellar-tendon rupture. *Journal of*
263 *Bone and Joint Surgery (American Volume)*. 1977;59A:179-183.

264

265 **FIGURES LEGEND**

266 Figure 1. Left column: Screenshots from one view showing the moment with the
267 greatest ankle inversion; Other columns: The ankle joint orientation presented in the
268 inversion/everion, plantarflexion/dorsiflexion and internal/external rotation planes.

269 Note that mirrored images of the injured right ankles in Case 2 and 4 were presented
270 for comparison with the injured left ankles in the other three cases.

271 Figure 2. Profile of joint orientation and angular velocity of ankle inversion, internal
272 rotation and plantarflexion in each injury incident.

273

274

275

276 **TABLE**

277 Table 1: Demographics of the five injury incidents in various tennis competitions in
 278 this study

| Case | Event | Gender | Injured limb | Camera views | Video frequency | Video resolution |
|------|--|--------|--------------|--------------|-----------------|------------------|
| 1 | Vienna 1995 | Male | Left | 2 | 50Hz | 320 x 240 |
| 2 | Monte Carlo Open, 1995 | Male | Right | 2 | 25Hz | 480 x 360 |
| 3 | German Open 2000, Berlin | Female | Left | 2 | 30Hz | 640 x 480 |
| 4 | Australian Open 2009, Melbourne | Female | Right | 2 | 30Hz | 416 x 320 |
| 5 | WTA Charleston Family Circle Cup, 2010 | Female | Left | 2 | 25Hz | 400 x 300 |

279

280

281

282 Table 2: Peak value of the ankle angles and velocities in each injury incident

| | This study | | | | | Fong et al | Mok et al 2011 | Kristianslund | |
|---------------------------------|------------|--------|---------|---------|--------|------------|----------------|---------------|------------|
| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | 2009 | Case 1 | Case 2 | et al 2011 |
| Peak inversion | 94° | 48° | 59° | 67° | 126° | 48° | 142° | 78° | ~35° |
| Peak inversion velocity | 1488°/s | 509°/s | 837°/s | 724°/s | 800°/s | 632°/s | 1752°/s | 1397°/s | 559°/s |
| Time of peak inversion | 0.12s | 0.08s | 0.12s | 0.17 | 0.44s | 0.20s | 0.08s | 0.08s | ~0.18s |
| Peak plantarflexion | 30° | 28° | 31° | 37° | -8° | 1° | ~52° | ~16° | ~20° |
| Peak plantarflexion velocity | 1748°/s | 381°/s | 561°/s | 571°/s | 325°/s | 370°/s | N/A | N/A | N/A |
| Time of peak plantarflexion | 0.16s | 0.10s | 0.03s | 0.46s | 0.07s | 0.04s | 0.18s | 0.17s | 0.30s |
| Peak internal rotation | 46° | 26° | 99° | 84° | 75° | 10° | ~50° | ~45° | ~55° |
| Peak internal rotation velocity | 1170°/s | 412°/s | 2124°/s | 1312°/s | 530°/s | 271°/s | N/A | N/A | N/A |
| Time of peak internal rotation | 0.26s | 0.06s | 0.12s | 0.26s | 0.41s | 0.20s | 0.15s | 0.12s | 0.16s |

283

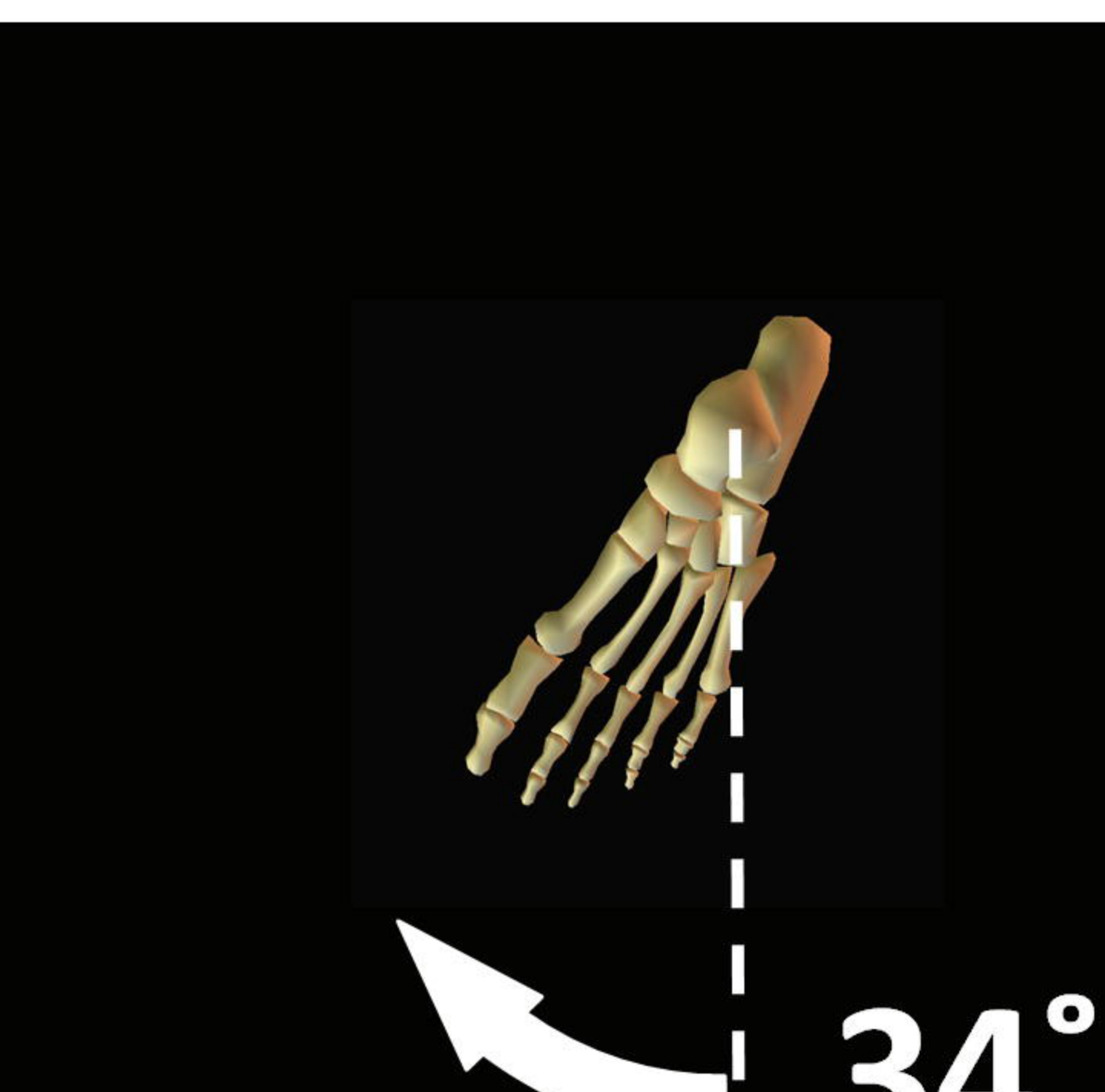
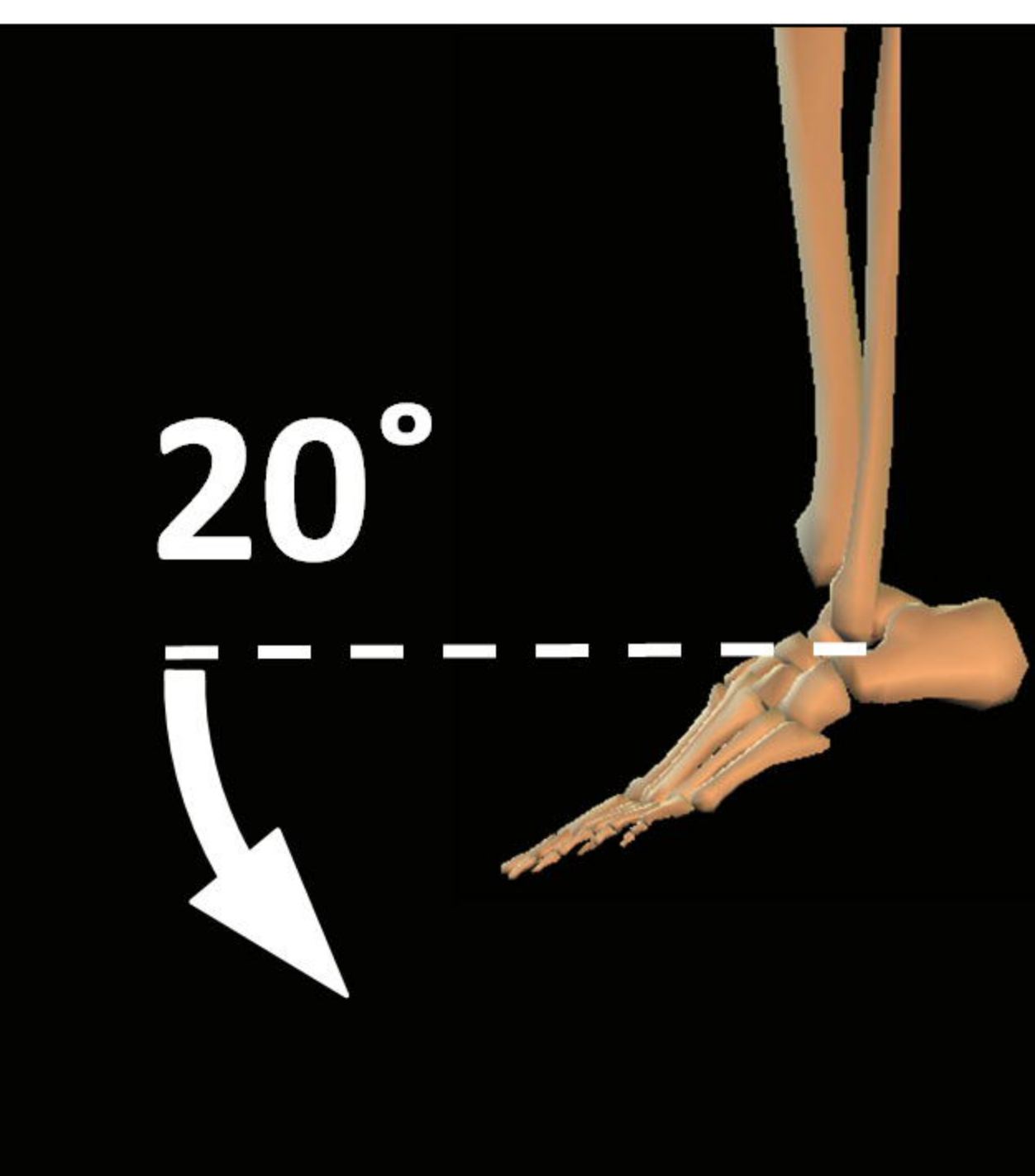
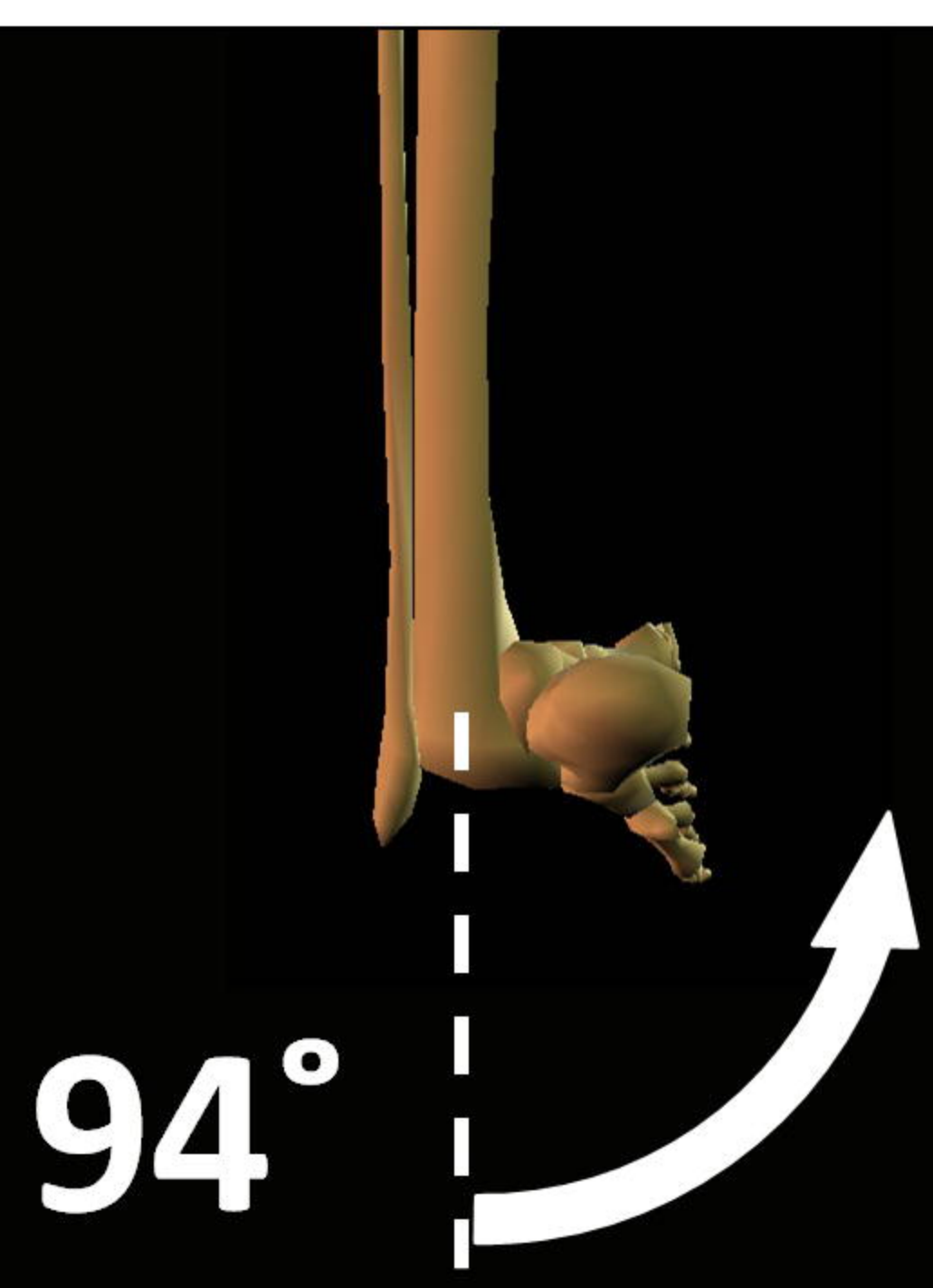
Video image with
matched skeleton

Inversion /
eversion

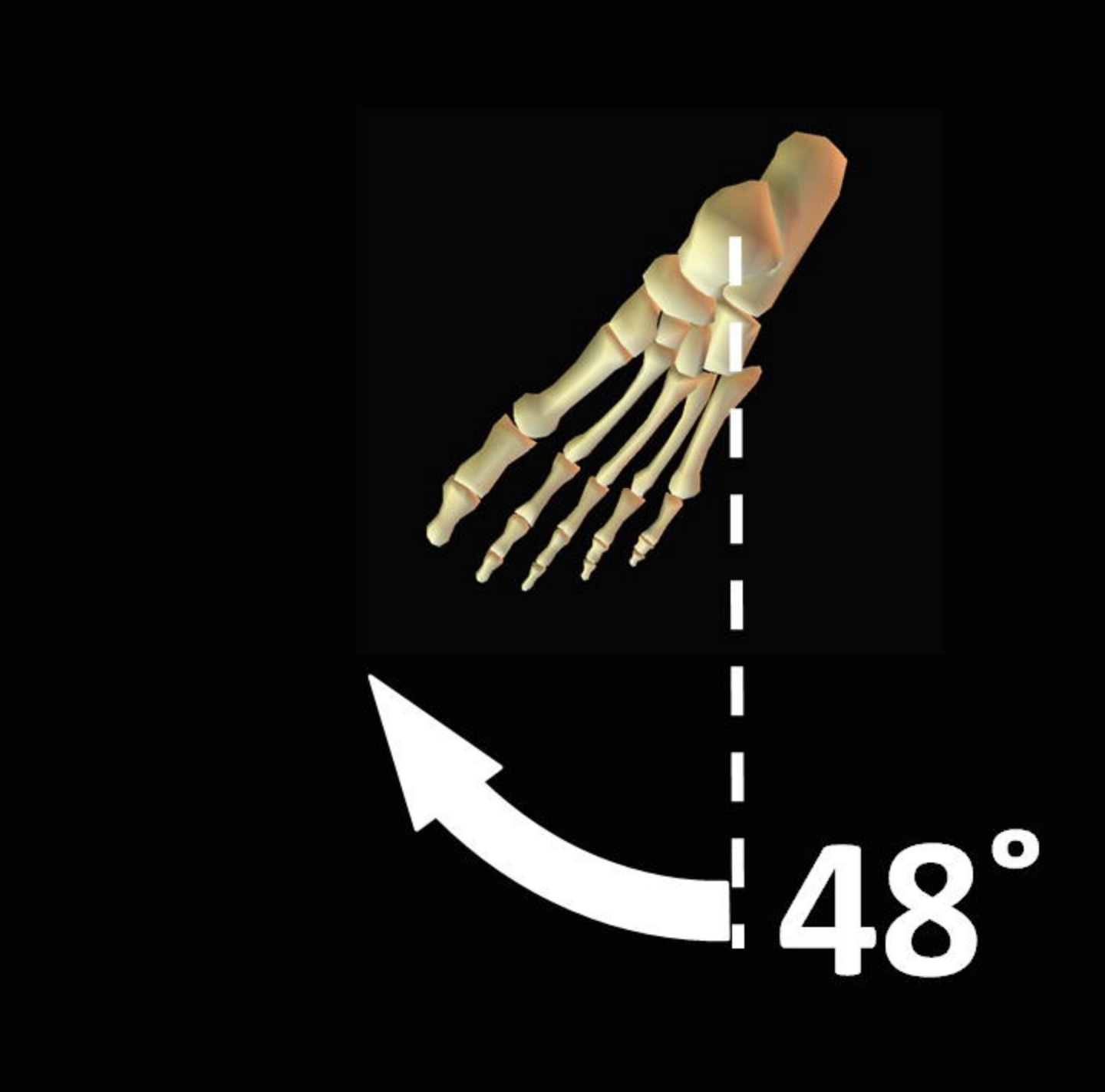
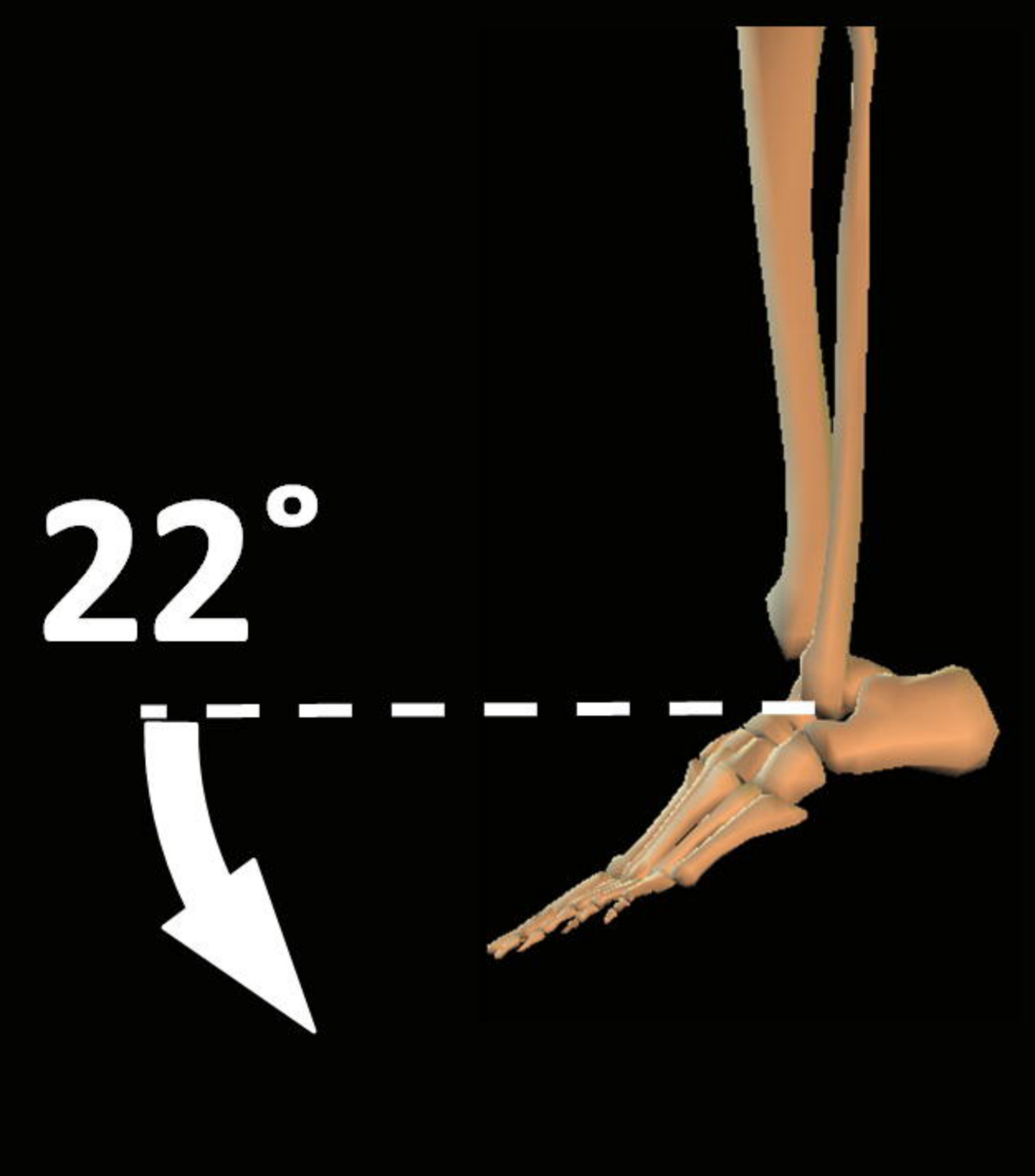
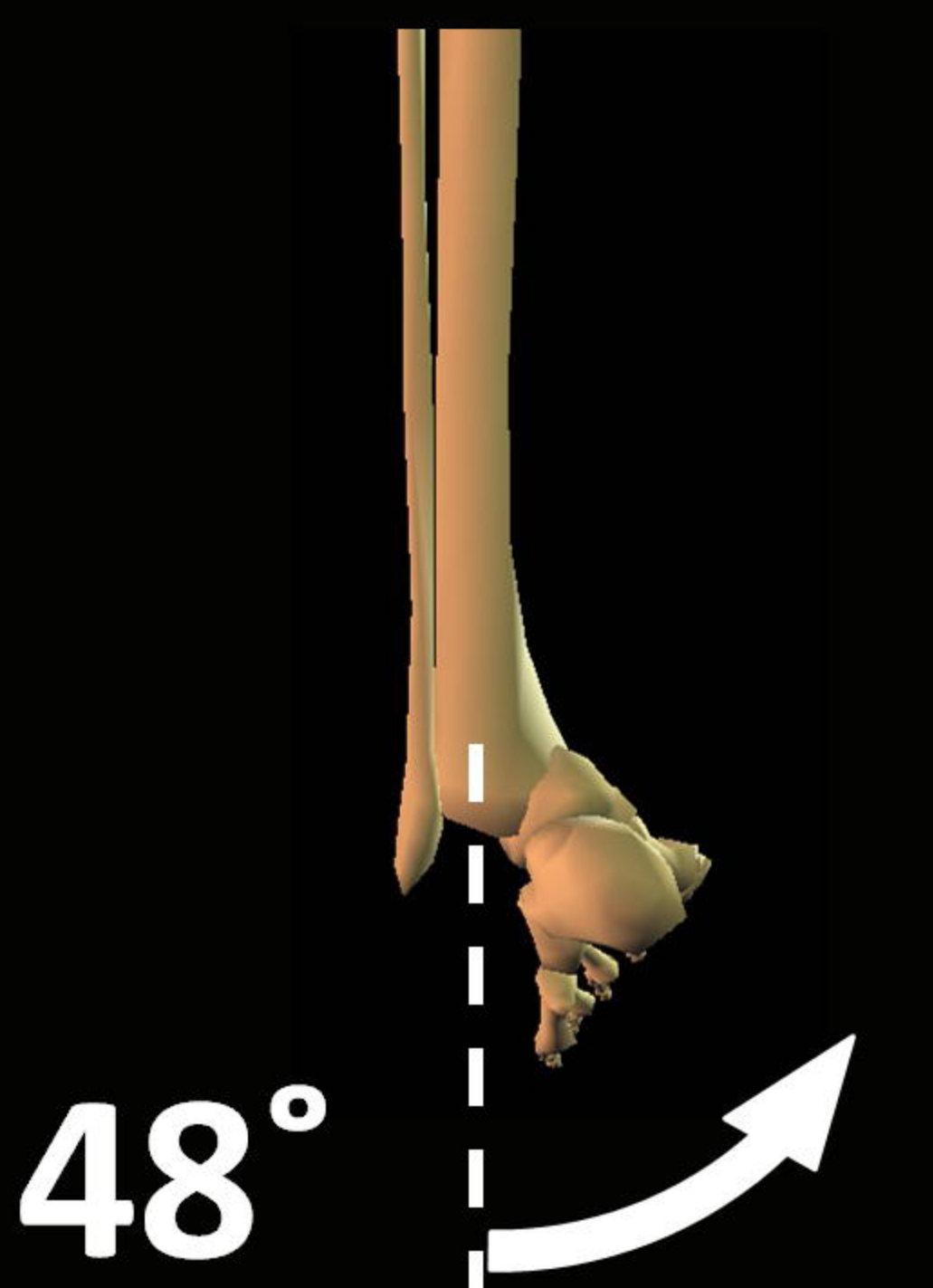
Plantarflexion /
dorsiflexion

Internal /
external rotation

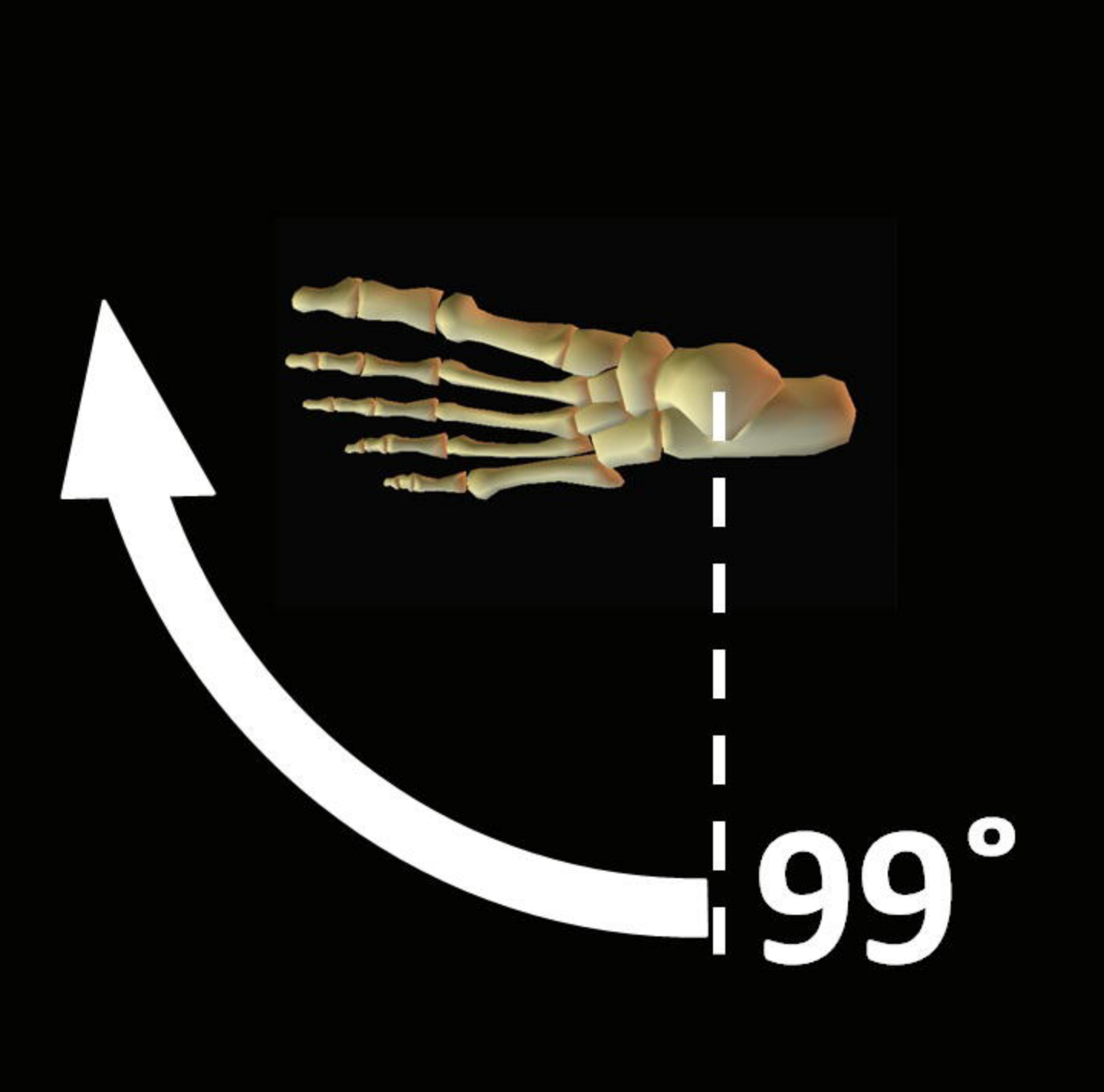
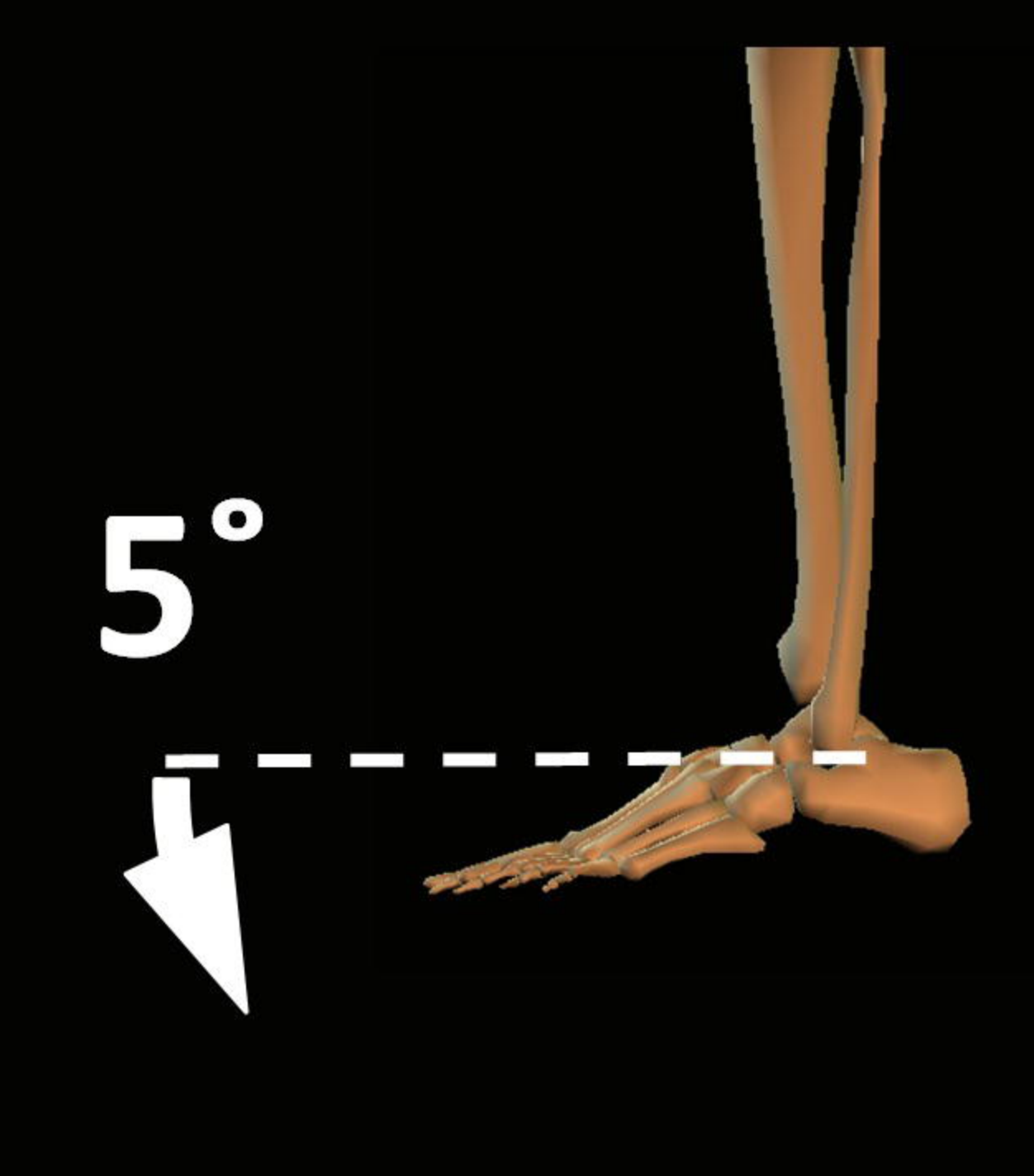
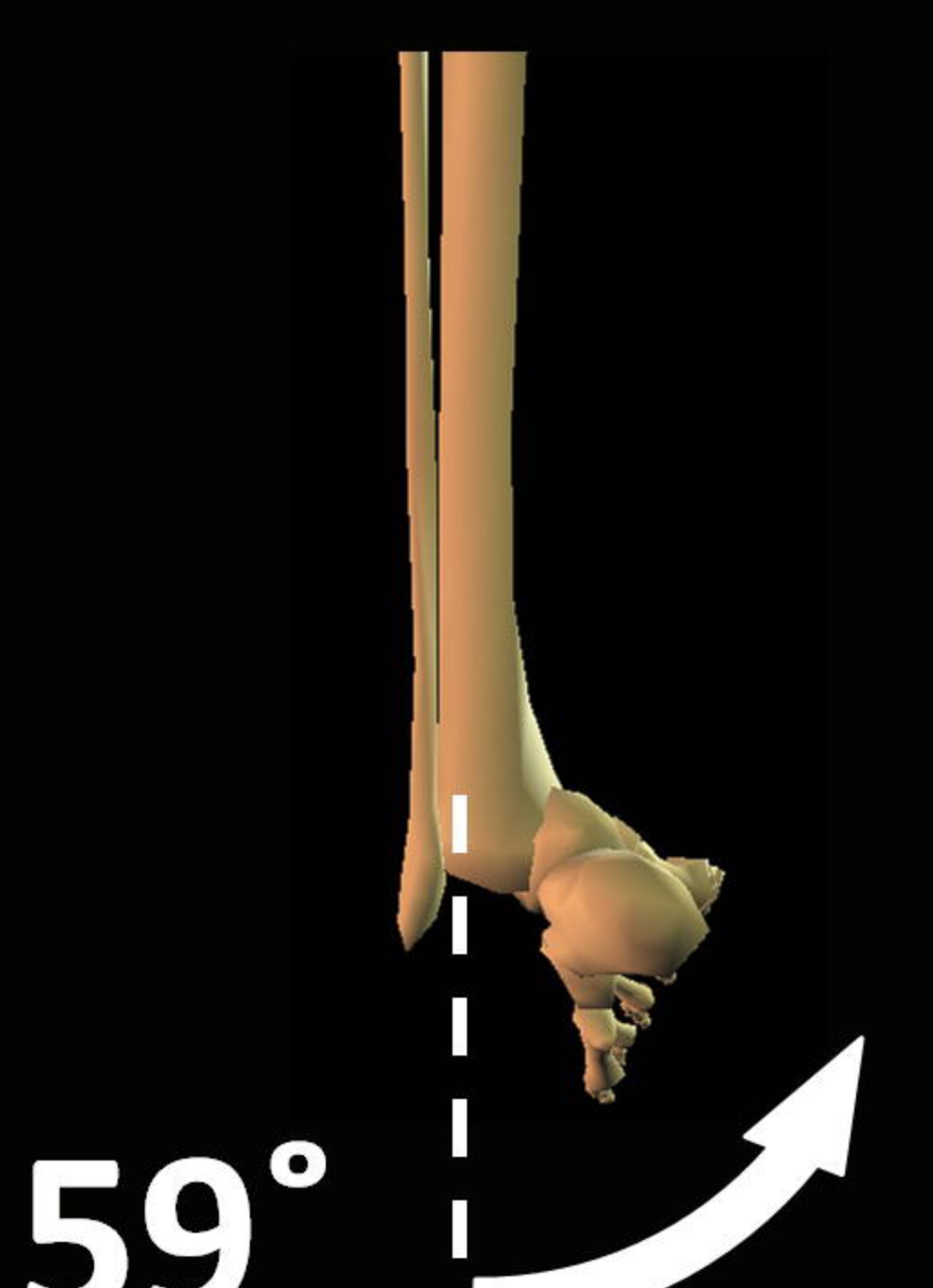
Case 1



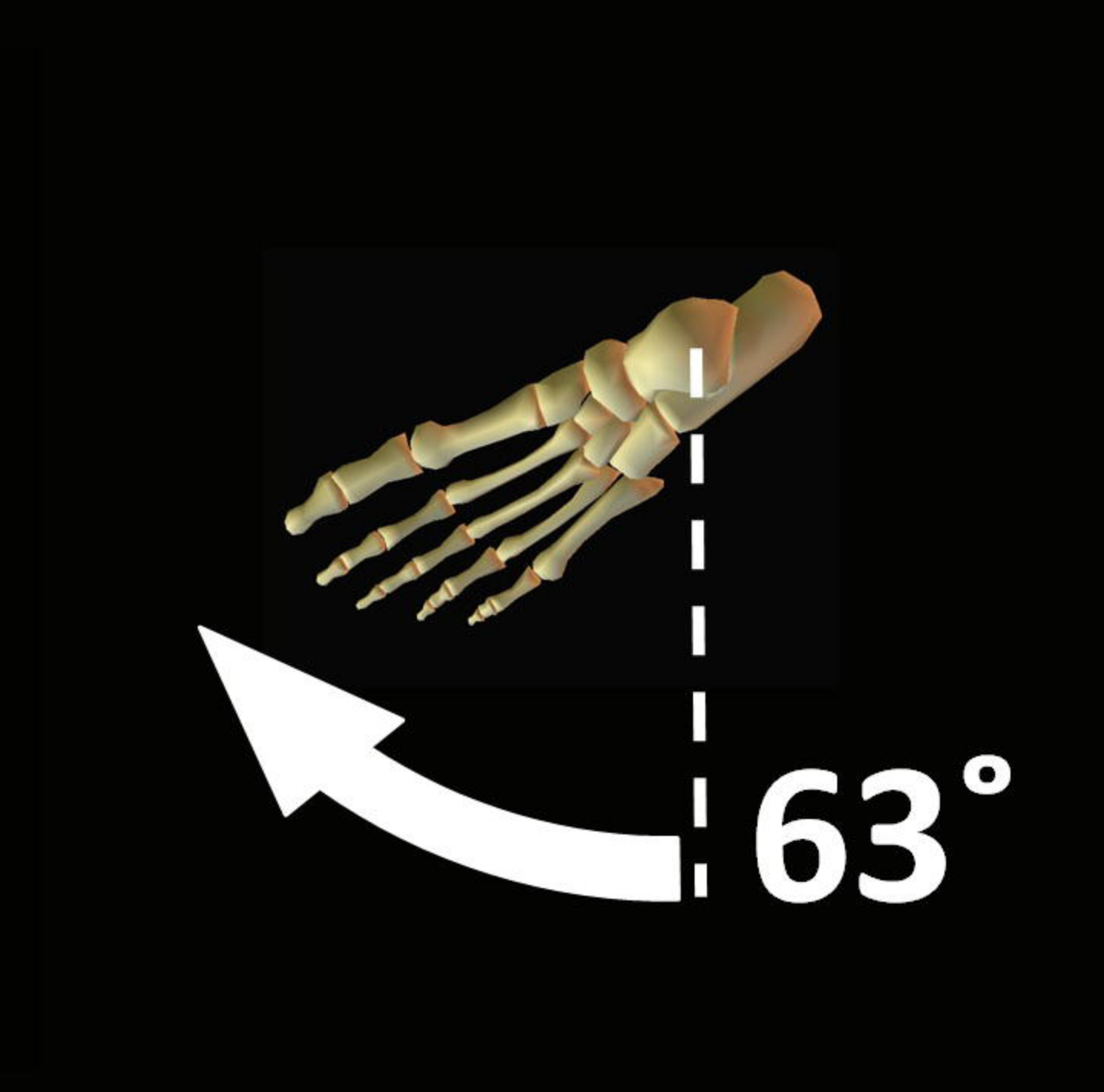
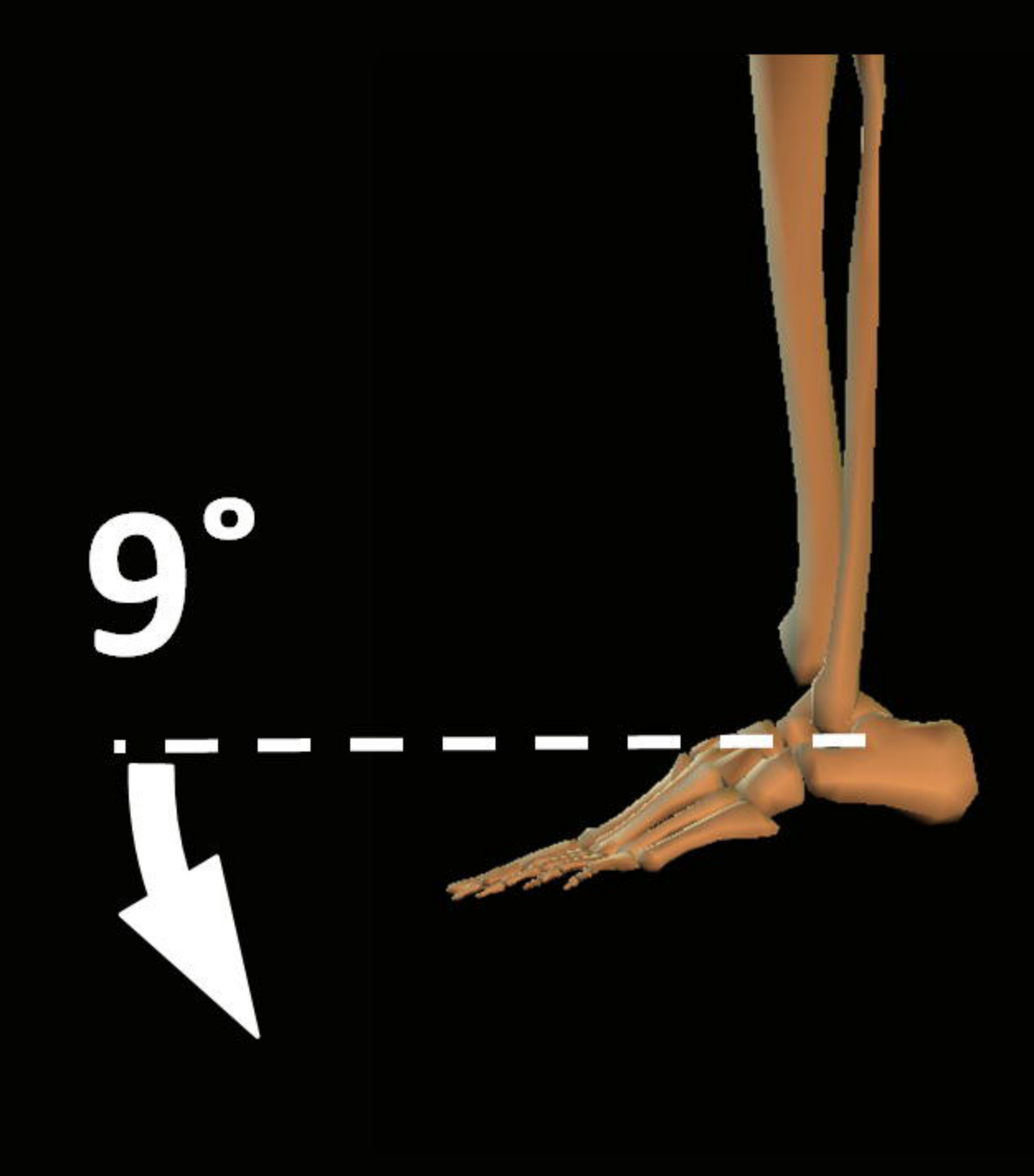
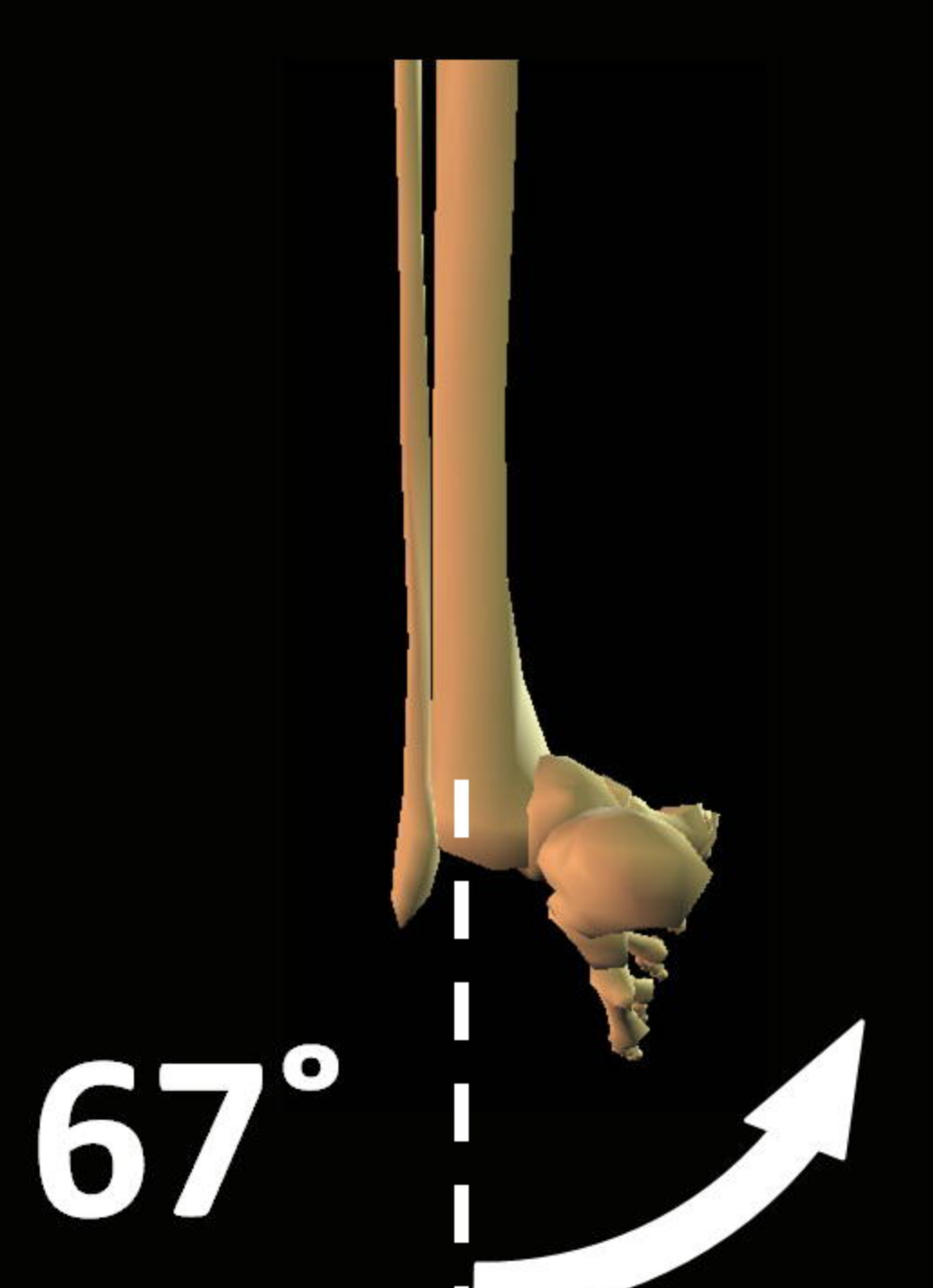
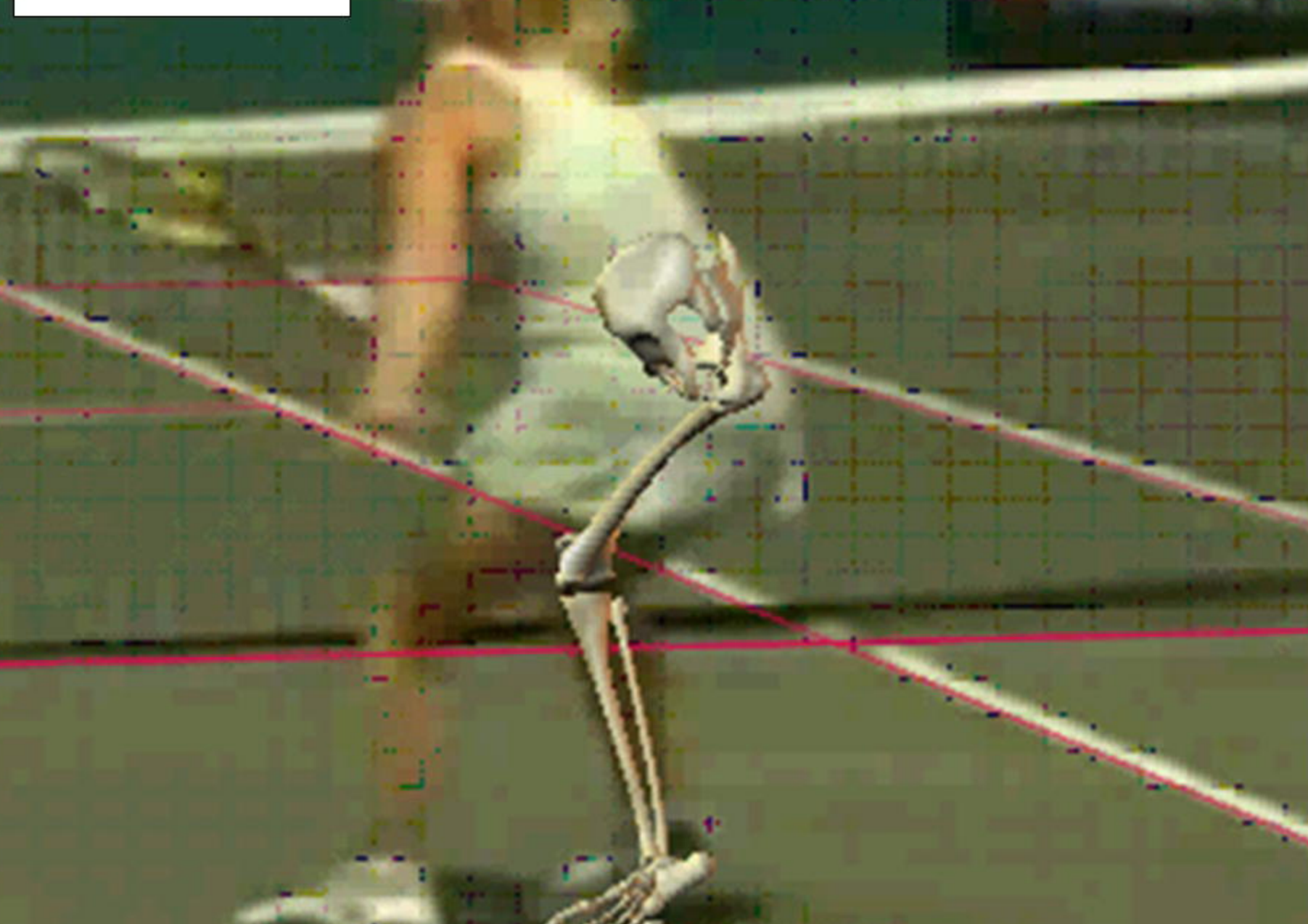
Case 2



Case 3



Case 4



Case 5

