

2014

A Review of Recent Perspectives on Biomechanical Risk Factors Associated with Anterior Cruciate Ligament Injury

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Recommended Citation

Hughes, Gerwyn, "A Review of Recent Perspectives on Biomechanical Risk Factors Associated with Anterior Cruciate Ligament Injury" (2014). *Kinesiology (Formerly Exercise and Sport Science)*. 48.
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1 **A review of recent perspectives on biomechanical risk factors associated with**
2 **anterior cruciate ligament injury.**

3

4 **Abstract**

5 There is considerable evidence to support a number of biomechanical risk factors
6 associated with non-contact anterior cruciate ligament (ACL) injury. This paper aimed
7 to review these biomechanical risk factors and highlight future directions relating to
8 them. Current perspectives investigating trunk position and relationships between
9 strength, muscle activity and biomechanics during landing/cutting highlight the
10 importance of increasing hamstring muscle force during dynamic movements through
11 altering strength, muscle activity, muscle length and contraction velocity. In particular,
12 increased trunk flexion during landing/cutting and greater hamstring strength are
13 likely to increase hamstring muscle force during landing and cutting which have been
14 associated with reduced ACL injury risk. Decision making has also been shown to
15 influence landing biomechanics and should be considered when designing tasks to
16 assess landing/cutting biomechanics. Coaches should therefore promote hamstring
17 strength training and active trunk flexion during landing and cutting in an attempt to
18 reduce ACL injury risk.

19

20 **Keywords:** strength, landing, trunk, knee.

21

22

23 **Introduction**

24 Anterior cruciate ligament (ACL) injury is a common debilitating sports injury which
25 often results in reduced knee function through the development of knee instability
26 and subsequent damage to the menisci and articular surfaces (Irvine & Glasgow,
27 1992; Smith, Livesay, & Woo, 1988). Approximately 70% of ACL injuries have been
28 reported to occur during non-contact situations, such as landing, deceleration and
29 rapid change of direction (Griffin et al., 2000). Females have been shown to be 6 to 8
30 times more likely to sustain an ACL injury compared to males competing in the same
31 sport (Arendt & Dick, 1995). A number of biomechanical risk factors have been
32 associated with this gender difference. Previous reviews have discussed gender
33 differences in kinematics and kinetics during landing or cutting manoeuvres (as
34 summarised in the first two sections of this review). However, more recent
35 perspectives, such as investigation of the role of the trunk, the effects of decision
36 making and the relationships between muscle strength, activity and landing/cutting
37 biomechanics, have received little consideration in previous reviews. The purpose of
38 this paper is to review the current evidence related to biomechanical risk factors
39 associated with the gender difference in the incidence of ACL injury and highlight
40 current perspectives relating to these biomechanical risk factors which require further
41 investigation.

42

43 **Gender differences in landing and cutting kinematics**

44 A number of studies which have investigated the sagittal plane kinematics of landing
45 and/or cutting manoeuvres report that females tend to contact the ground with the
46 hips and knees more extended than males (Decker, Torry, Wyland, Sterett, &

47 Steadman, 2003; James, Sizer, Starch, Lockhart, & Slauterbeck, 2004; Malinzak,
48 Colby, Kirkendall, Yu & Garrett, 2001; Yu, Lin, & Garrett, 2006). Contraction of the
49 quadriceps, acting through the patellar tendon, produces an anteriorly directed shear
50 force to the proximal tibia. For a given load acting through the patellar tendon, the
51 less knee flexion, the greater the strain on the ACL is likely to be due to the inverse
52 relationship between knee flexion and the patella tendon-tibia shaft angle (angle
53 between the long axis of the tibia and the line of action of the patellar tendon in the
54 sagittal plane) (Li et al., 1999; Nunley, Wright, Renner, Yu, & Garrett, 2003).
55 Furthermore, as knee flexion angle decreases, hamstring tendon-tibia shaft angle
56 has been shown to decrease to the point where hamstring muscle force may
57 increase the anterior shear force acting at the proximal tibia when the knee is close
58 to full extension (Lin et al., 2012). Non-contact ACL injury has been reported to occur
59 frequently when the knee is close to full extension (Boden, Dean, Feagin, & Garrett,
60 2000; Olsen, Mykelbust, Engebretsen, & Bahr, 2004). Consequently, reduced knee
61 flexion at initial ground contact in females may increase the risk of ACL injury relative
62 to males.

63

64 Studies which have investigated the frontal plane kinematics of landing/cutting report
65 females to exhibit greater maximum knee valgus angle and greater range of motion
66 of knee valgus when landing compared to males (Ford, Myer, & Hewett, 2003;
67 Hughes, Watkins, & Owen, 2008; Kernozek, Torry, Van Hoof, Cowley, & Tanner,
68 2005; Malinzak et al., 2001). Due to the structure of the knee, angular motion about
69 an anteriorposterior axis (knee valgus/varus) is very limited, whereby the hamstring
70 muscles tend to stabilise the knee the frontal plane (Lloyd & Buchanan, 2001).
71 Excessive valgus movement of the knee is likely to indicate reduced dynamic stability

72 provided by the hamstrings and result in strain acting on the passive support
73 structures, in particular the ACL. Boden et al. (2000) and Olsen et al. (2004) reported
74 that non-contact ACL injury frequently occurs when the knee exhibits a valgus
75 movement. Consequently, the greater maximum knee valgus angle and range of
76 motion of knee valgus reported in females during landing/cutting may increase the
77 risk of ACL injury relative to males. Finally, Pollard, Sigward, & Powers (2010)
78 reported that female subjects who exhibited low peak flexion angles (combined knee
79 and hip flexion) during landing displayed significantly greater peak knee valgus
80 angles. This suggests there may be an association between frontal and sagittal plane
81 kinematics at the knee during landing which combine to increase ACL injury risk in
82 females.

83

84 **Gender differences in landing and cutting kinetics**

85 During landing, lower limb joint movements are determined by the resultant joint
86 moments acting about the joints. Studies examining internal joint moments (moment
87 produced about a joint by the internal structures within and crossing a joint) of the
88 lower limbs during landing indicate that females tend to exhibit reduced hip extension
89 moment and greater knee extension moment (Chappell, Yu, Kirkendall, & Garrett,
90 2002; Salci, Kentel, Heycan, Akin, & Korkusus, 2004; Yu et al., 2006) than males,
91 even when accounting for differences in body size. In the frontal plane, females tend
92 to exhibit greater knee valgus moments during landing/cutting compared to males
93 (Chappell et al., 2002; Earl, Monteiro, & Snyder, 2007; Kernozek, et al., 2005;
94 McLean, Huang, & van den Bogert, 2005; McLean, Walker, & van den Bogert, 2005;
95 Pappas, Hagins, Sheikzadeh, Nordin, & Rose, 2007). Knee valgus moments have

96 been shown to cause high loading of the ACL (Markolf et al., 1995; Mizuno, Andrish,
97 van den Bogert, & McLean, 2009).

98

99 The internal moment about a particular axis through a joint is the predominantly
100 determined by the moment due to the various muscles which, in turn, depends on
101 both the muscle forces and the moment arms of the muscles. Figure 1 shows the
102 forces acting on the proximal end of the tibia due to the ACL, posterior cruciate
103 ligament (PCL), quadriceps and hamstrings and their moment arms in the sagittal
104 plane when the knee is close to full extension, i.e., when non-contact ACL injury is
105 most common.

106

107 Figure 1 about here.

108

109

110 Kellis and Baltzopoulos (1999) calculated the moment arms of the patella tendon and
111 the hamstrings for ten male subjects in the sagittal plane during submaximal knee
112 flexion-extension movement at very slow (non constant) angular velocity using
113 videofluoroscopy. Moment arms were taken as the perpendicular distance between
114 the muscle tendon and the central contact point of the tibiofemoral joint. Between 0-
115 10° of knee flexion, the mean moment arm of the patella tendon was found to be 36.9
116 ± 3.2 mm and the mean moment arm of the hamstrings was found to be 23.9 ± 2.6
117 mm. Other studies report values ranging from 30 mm to 40 mm for the moment arm
118 of the patella tendon (Grood, Suntay, & Noyes, 1984; Herzog & Read, 1993; Smidt,
119 1973) and ranges from 20 mm to 41.3 mm for the moment arm of the hamstrings

120 (Herzog & Read, 1993; Smidt, 1973; Wretenburg, Nemeth, Lamontagne, & Lundin,
121 1996). These data suggests that the mechanical advantage of the quadriceps may
122 be greater than that of the hamstrings. When the knee is in a flexed position
123 (between 15° and 60° of knee flexion), since the hamstrings work with the ACL to
124 prevent anterior dislocation of the proximal tibia relative to the distal femur (Li et al.,
125 1999), this reduced mechanical advantage of the hamstrings relative to the
126 quadriceps may increase the risk of overloading the hamstring muscles, which in turn
127 may cause increased anterior shear force on the proximal end of the tibia which may
128 strain the ACL. However, at low knee flexion angles (less than 15°), co-contraction of
129 the hamstrings has been shown to not significantly reduce tibia anterior translation (Li
130 et al., 1999).

131

132 Figure 2 shows the forces acting on the proximal end of the tibia due to the ACL,
133 PCL, semimembranosus, semitendinosus, gracilis and biceps femoris and their
134 moment arms in the frontal plane when the knee is close to full extension, i.e., when
135 non-contact ACL injury is most common.

136 _____

137 Figure 2 about here.

138 _____

139

140 Wretenburg et al., (1996) calculated the moment arms of the semimembranosus,
141 semitendinosus, gracilis and biceps femoris in the frontal plane for ten male and
142 seven female subjects using MRI measurements. Moment arms were taken as the
143 perpendicular distance between the muscle tendon and the central contact point of

144 the tibiofemoral joint and were measured with no muscle contraction. The absolute
145 moment arms of the semimembranosus, semitendinosus, gracilis and biceps femoris
146 in the frontal plane were significantly greater in males than females. Even when
147 normalised to height, the moment arms of all muscles were still greater in males than
148 females. These data suggests that the mechanical advantage of the
149 semimembranosus, semitendinosus, gracilis and biceps femoris in the frontal plane
150 may be greater in males than females. Since these muscles work with the passive
151 support structures of the knee to prevent abnormal movement of the knee joint in the
152 frontal plane (Lloyd & Buchanan, 2001), this reduced mechanical advantage in
153 females compared to males may increase the risk of overloading the
154 semimembranosus, semitendinosus, gracilis and biceps femoris, which in turn may
155 increase the likelihood of an abnormal movement of the knee joint in the frontal plane
156 which may strain the passive support structures of the knee.

157

158 In summary, ACL injury is likely to occur due to abnormal movement of the
159 tibiofemoral joint. In the sagittal plane, an imbalance of quadriceps muscle force over
160 hamstring muscle force resulting in anterior shear force acting on the proximal end of
161 the tibia is likely to cause an abnormal movement of the tibiofemoral joint (anterior
162 displacement of the tibia relative to the femur) which will increase ACL strain. The
163 greater knee extension moment in females compared to males suggests females'
164 quadriceps muscles produce greater force relative to the force due to the hamstrings
165 than males. Therefore future research should focus on ways to increase knee flexion
166 angle and reduce knee extension and valgus moments in females through increasing
167 hamstring muscle forces, in particular those muscles which attach to the medial
168 aspect of the tibia. Recent perspectives on examining biomechanical risk factors

169 associated with ACL injury have focussed on investigation of the role of the trunk, the
170 effects of decision making and the relationships between muscle strength, activity
171 and landing/cutting biomechanics. Whilst many of the studies focussing on these
172 recent perspectives have identified relationships between these independent
173 variables and biomechanical variables that have previously been identified as being
174 associated with the gender difference in ACL injury incidence (as described
175 previously), limited direct investigation into gender effects has been conducted.
176 Therefore it is proposed that future research should be conducted in these areas to
177 clearly identify if gender differences exist within these new perspectives.

178

179 **The effects of trunk position and load on landing/cutting biomechanics**

180 Through analysis of videos in which ACL injury occurred, Hewett, Torg and Boden
181 (2009) identified that non-contact ACL injury was associated with reduced forward
182 trunk lean and greater trunk lateral flexion, where the body was shifted towards the
183 landing leg at the time of injury. This is also supported by Boden et al., (2000) who
184 found that at the time of ACL injury the trunk tended to be upright and/or laterally
185 flexed. Zazulak, Hewett, Reeves, Goldberg and Cholewicki (2007) prospectively
186 examined the relationship between trunk control and ACL injury by measuring trunk
187 displacement after the release of a sudden force in a group of 277 collegiate athletes.
188 Of the athletes measured, 25 sustained a knee injury and 6 sustained ACL injury (4
189 females and 2 males). Trunk displacements at 150 ms following release of the force
190 and maximum trunk displacement were significantly greater in the knee injured,
191 ligament injured and ACL injured groups compared to the non injured athletes. Of the

192 variables analysed, lateral displacement of the trunk was the strongest predictor of
193 ligament injury.

194

195 Trunk flexion is likely to influence lower extremity biomechanics through altering hip
196 extensor and knee flexor muscle function (Grasso, Zago, & Lacquaniti, 2000;
197 Lieberman, Raichlen, Pontzer, Bramble, & Cutright-Smith, 2006; Paul, Salle, &
198 Frings-Dresen, 1996) and altering the moment due to the trunk about the lower
199 extremity joints (Blackburn & Padua, 2009). Flexion of the trunk is often accompanied
200 by anterior pelvic tilt. Anterior pelvic tilt will lengthen the gluteus maximus muscle and
201 the hamstring muscle group, influencing the force-length relationship of the these
202 muscles, whereby these muscles are positioned in such a way as to increase their
203 ability to exert force (Kulas, Hortobagyi, & Devita, 2010). Therefore, increased trunk
204 flexion during landing/cutting is likely to result in increased length of the hamstrings
205 and gluteus maximus than when landing with less trunk flexion which, in turn, will
206 increase muscle forces. This increased force production of the gluteus maximus and
207 the hamstrings may result in increased hip extension moment, reduced knee
208 extension moment and reduced knee valgus moment during landing, all of which
209 have been proposed to be associated with reduced ACL loading (Chappell et al.,
210 2002; Salci et al., 2004; Yu et al., 2006).

211

212 Trunk flexion is likely to influence the moment due to the trunk about the hip and
213 knee in the sagittal plane. This occurs due to the centre of mass of the trunk moving
214 forward with increased trunk flexion, causing the centre of mass of the trunk to move
215 closer to the knee and further away from the hip in the horizontal plane. Since the

216 moment due to the trunk will be the product of the weight of the trunk and the
217 horizontal distance between the centre of mass of the trunk and the joint centre (i.e.
218 the moment arm of the trunk), increased trunk flexion is likely to increase the moment
219 due to the trunk about the hip but decrease the moment due to the trunk about the
220 knee (Blackburn & Padua, 2009).

221

222 Due to these factors, recent research examining lower extremity biomechanical risk
223 factors associated with ACL injury has therefore focused on the influence of trunk
224 load and trunk motion (Blackburn & Padua, 2009; Chaudhari, Hearn, & Andriacchi,
225 2005; Dempsey, Elliott, Munro, Steele, & Lloyd, 2012; Janssen, Sheppard, Dingley,
226 Chapman, & Spratford, 2012; Kulas, et al., 2010; Kulas, Zalewski, Hortobagyi, &
227 Devita, 2008; Nagano, Ida, Akai, & Fukubayashi, 2011; Shimokochi, Ambegaonkar,
228 Meyer, Lee, & Shultz, 2013). A summary of the reported effects of trunk flexion and
229 trunk loading on lower extremity biomechanics during landing/cutting manoeuvres is
230 shown in Table 1.

231

232 Table 1 about here.

233

234

235 The findings of these studies provide strong evidence that trunk loading and trunk
236 position alters the lower extremity biomechanical risk factors associated with ACL
237 injury. In particular, increased trunk load and reduced trunk flexion have been shown
238 to be associated with increased knee anterior shear force during two-footed landing
239 (Kulas et al., 2010) and increased ACL forces during single-leg squats (Kulas,

240 Hortobagyi, & DeVita, 2012). Initial findings examining relationships between frontal
241 and transverse plane motion of the trunk with frontal plane loading of the knee when
242 in single limb stance show some association between these variables. Chaudhari et
243 al. (2005) report that preventing weight from moving over the plant leg through
244 constraining arm movement may increase knee valgus loading in cutting whereas
245 Dempsey et al. (2012) report a significant positive correlation between trunk lateral
246 flexion towards landing leg and knee valgus moment during single leg landing.
247 Furthermore, Frank et al. (2013) reported increased knee varus moments were
248 associated with limited trunk rotation away from the stance limb and towards the
249 direction of travel during a cutting task. Therefore, further investigation is required to
250 verify the relationship between trunk movement and knee loading in the frontal and
251 transverse planes during different tasks in which ACL injuries frequently occur and
252 further investigation is required to determine whether gender differences exist in
253 trunk position during landing and cutting which may contribute to the gender
254 difference in ACL injury incidence.

255

256 **The relationships between muscle activity, strength and landing/cutting** 257 **biomechanics**

258 During landing and cutting, while the quadriceps muscles contract to attempt to
259 control knee flexion through eccentric contraction, co-contraction of the hamstrings is
260 essential to prevent excessive ACL loading due to the anterior shear force produced
261 by the quadriceps. Due to their attachments on the lateral and medial aspects of the
262 tibia, the hamstring muscles also help control transverse and frontal plane motions of
263 the knee (Lloyd & Buchanan, 2001). For example, Louie and Mote (1987) found that

264 co-contraction of the muscles surrounding the knee increased torsional stiffness of
265 the knee joint and Olmstead, Weavers, Bryant, and Gouw (1986) found that
266 contraction of the hamstrings to produce a relatively small flexion torque at the knee
267 (less than 20% maximum torque) increased valgus stability of the knee. A
268 combination of anterior shear force acting on the proximal tibia and valgus loading
269 result in loading of the ACL exceeds the loading due to each of these factors
270 independently (Berns, Hull, & Patterson, 1992; Markolf et al., 1995) which further
271 highlights the important role of the hamstring muscle group in the prevention of non
272 contact ACL injury. A number of studies have reported females to possess lower
273 strength of the hamstrings compared to males, even when normalised to body weight
274 (Hakkinen, Kraemer, & Newton, 1997; Huston & Wojtys, 1996; Salci et al., 2004).
275 Furthermore, lower hamstring to quadriceps strength ratio's have been observed in
276 females compared to males and have been reported to be due to reduced hamstring
277 strength in females rather than due to differences in quadriceps strength (Myer et al.,
278 2009). Lower hamstring to quadriceps strength ratio's have been reported to be
279 associated with greater frontal and transverse plane motion during dynamic activities
280 (Hewett et al., 2005). Since muscle strength is modifiable, Hewett et al. (1996)
281 investigated the effect of a plyometric training intervention on landing mechanics and
282 lower limb strength. The results showed plyometric training significantly increased
283 hamstring strength which was also associated with significant reductions in frontal
284 plane knee loading during a landing task. However, recent reviews of the effects of
285 training programs on ACL injury (Dai, Herman, Lui, Garrett, & Yu, 2012; Donnelly et
286 al., 2012) highlight that whilst many training programs result in altered lower
287 extremity movement patterns, the effect of these training programs on ACL injury
288 incidence is inconsistent and the mechanisms by which biomechanical risk factors

289 are influenced by training is unclear. Furthermore, a systematic review by Stojanovic
290 and Ostojic (2012) examining nine studies which investigated the effects of training
291 on ACL injury concluded that multicomponent training programs which included
292 balance, plyometrics, agility and strength components appeared to be the most
293 effective. However, more research is required to further verify the effects of training
294 programs on ACL injury incidence in both males and females.

295

296 The force a muscle produces during a landing or cutting manoeuvre depends on a
297 number of factors; including muscle length, contraction velocity, muscle strength
298 (maximal force output) and muscle activity (number of active motor units and their
299 firing rate). Previous research indicates gender differences exist in muscle activity
300 during landing/cutting, whereby females tend to exhibit greater quadriceps muscle
301 activity and less hamstring muscle activity compared to males (Malinzak et al., 2001)
302 which is likely to result in increase ACL loading. Recent research has attempted to
303 explore the relationships between strength, muscle activity and landing
304 biomechanics. For example, Wild et al. (2013) examined lower limb kinematics of the
305 hip, knee and ankle, ACL forces and muscle activity of six lower limb muscles
306 (Medial Gastrocnemius, Tibialis Anterior, Vastus Medialis, Rectus Femoris,
307 Semitendinosis and Biceps Femoris) during a single-leg horizontal landing in high (n
308 = 11) and low (n = 11) concentric hamstring strength groups of pubescent females.
309 The results showed that the low hamstring strength group displayed significantly
310 greater knee valgus angles at the time of maximum vertical and anteroposterior
311 ground reaction forces (GRF), significantly less hip abduction moments at the time of
312 maximum vertical GRF and significantly greater ACL force at the time of maximum
313 anteroposterior GRF compared to the high hamstring strength group. No significant

314 differences were observed in the time of onset of muscle activity and the time to peak
315 amplitude between high and low strength groups. These results suggest that those
316 with low hamstring strength display a reduced ability to control frontal plane
317 alignment of the lower limb during landing despite similar timing of muscle activity.
318 Therefore, for the muscles that control the stability and movement of the knee,
319 differences in peak strength may have a greater influence on the prevention of
320 excessive frontal plane motion and ACL force than differences in the timing of muscle
321 activity, however further investigation is needed to examine the magnitude of muscle
322 activity to further investigate these relationships.

323

324 Since reduced hip extension moment and increased knee extension moment have
325 been associated with the gender difference in the incidence of ACL injury, Stearns et
326 al. (2013) examined the relationship between hip and knee extension isometric
327 strength and extension moments of the hip and knee observed during a two-footed
328 drop-jump task in 20 male and 20 female recreational athletes. The results showed
329 females displayed a significantly greater knee to hip extension moment ratio during
330 landing and a significantly greater knee to hip extension isometric strength ratio
331 compared to males. The results also showed that there was a significant positive
332 relationship between landing knee to hip extension moment ratio during landing and
333 knee to hip isometric strength ratio. These findings suggest that gender differences in
334 hip and knee extensor moments observed during landing may partly be explained by
335 differences in strength and therefore strengthening of the muscles that control hip
336 extension (Hamstrings and Gluteus Maximus) in females may be important to reduce
337 the gender difference in the incidence on non-contact ACL injury.

338

339 The hip external rotators and abductors help prevent excessive valgus knee motion
340 during landing through eccentric control of the femur. Weakness and/or insufficient
341 activation of these muscles in females may also contribute to the greater incidence of
342 non-contact ACL injury in females. Some studies have found an association between
343 reduced hip abduction and external rotation strength and increased knee valgus
344 motion during landing (Jacobs, Uhl, Mattacola, Shapiro, & Rayens, 2007; Wallace et
345 al., 2008), however other studies have contradicted these findings (Bolgia, Malone,
346 Umberger, & Uhl, 2008; Lawrence, Kernozek, Miller, Torry, & Reuteman, 2008;
347 Patrek, Kernozek, Willson, Wright, & Doberstein, 2011). The reason for the
348 discrepancy between these studies may, in part, be due to a lack of association
349 between the muscle force produced during a dynamic task and strength during
350 isometric or isokinetic tests, since other factors will also influence muscle force during
351 a dynamic task. Therefore, Homan et al. (2013) measured hip external rotation and
352 abduction isometric strength and examined relationships between these factors and
353 gluteal muscle activity, frontal plane angles of the hip and knee and transverse plane
354 motion of the hip during a two legged drop jump landing. For hip abduction strength,
355 no significant differences were observed in landing kinematics of the hip and knee
356 between high and low strength groups, however, the high hip abduction strength
357 group displayed significantly less gluteus medius EMG amplitude compared to the
358 low strength group. For hip external rotation strength, the high strength group
359 exhibited significantly less external rotation, valgus knee angles and gluteus
360 maximum muscle activity than the low strength group. These results therefore
361 suggest that individuals with reduced hip abduction strength may compensate for
362 strength deficiencies through increased activation the hip abductors in an attempt to
363 maintain frontal plane alignment during landing.

364

365 Overall, studies examining the relationships between lower limb strength, muscle
366 activity and landing/cutting biomechanics suggest that strengthening the hamstring
367 muscles can be important in preventing ACL injury through enhanced ability to
368 control frontal plane motion and loading of the knee and reducing the net knee
369 extension moment during landing/cutting. There is less evidence to support the
370 relationship between hip abduction and external rotation strength in controlling knee
371 motion and loading, suggesting that the activity of these muscles may be more
372 important in controlling frontal plane motion of the knee, however further research is
373 required to confirm these findings.

374

375 **The effects of decision making on landing/cutting biomechanics**

376 Initial research examining gender differences in landing and cutting biomechanics
377 have used highly standardised tasks which are predictable and controlled, such as
378 drop-landings and drop-jumps from a set height (Decker et al. 2003; Kernozek et al.,
379 2005; Salci et al., 2004) or cutting at a pre-determined angle (James et al., 2004;
380 Malinzak et al., 2001). Whilst these standardised tasks have allowed us a greater
381 understanding of biomechanical risk factors associated with ACL injury through
382 controlling a number of potentially confounding factors, minor variations in jump
383 landing tasks have been show to significantly affect landing biomechanics (Cruz et
384 al., 2013). These tasks do not reflect the random nature of sports where participants
385 are often required to respond to a number of different stimuli simultaneously and
386 have to make adjustments during landing/cutting activity in response to these stimuli.
387 This has led to recent research examining landing biomechanics during anticipated

388 and unanticipated tasks to investigate the effects of decision making on landing
389 biomechanics (Brown, Palmieri-Smith, & McLean, 2009; Houck, Duncan, & De
390 Haven, 2006; Mache, Hoffman, Hannigan, Golden, & Pavol, 2013; McLean,
391 Borotikar, & Lucey, 2010). For example, Houck et al., (2006) compared trunk
392 orientation in the frontal plane (trunk position relative to the global vertical position),
393 trunk lateral flexion (trunk position relative to the pelvis segment), lateral foot
394 placement, frontal plane hip angle along with hip and knee moments in the frontal
395 plane during anticipated and unanticipated straight line walking and side cutting
396 (approximately 50° change of direction) tasks. The results showed that frontal plane
397 trunk orientation was significantly greater and hip abduction was significantly lower
398 during the unanticipated side-step task compared to all other tasks whereas trunk
399 lateral flexion was relatively similar across all tasks. Frontal plane knee moments
400 were also affected by the decision making, whereby close to initial ground contact,
401 moments were in the valgus direction during unanticipated side-cutting compared to
402 the moments being in the varus direction for all other tasks and knee valgus
403 moments were lower during 10-30% of stance for unanticipated side-cutting task
404 compared to when the side cut was anticipated. These findings suggest that frontal
405 plane hip and knee biomechanics are affected by anticipation and that global trunk
406 orientation is affected by altered lower limb positioning rather than by trunk lateral
407 flexion during unanticipated cutting. However, the speed of the walking and cutting
408 activities were fairly low (means of between 2.2 m/s and 1.9 m/s). Since ACL injury is
409 likely to occur during more dynamic activities it limits the validity of the findings of this
410 study and more research needs to be done in activities more representative of tasks
411 in which ACL injury is common. Also, as with Mache et al., (2013), all unanticipated
412 task were completed after the anticipated tasks. The non-randomised order of the

413 pre-planned and decision making conditions suggest that learning and fatigue effects
414 may have occurred, limiting the strength of any conclusions made.

415

416 Decision making has also been found to influence knee valgus moment by McLean
417 et al., (2010) who found the knee valgus moment measured during unanticipated
418 single leg landings (stimulus for which leg to land on given approximately 650 ms
419 before ground contact) was significantly greater than during anticipated single leg
420 landings (stimulus for which leg to land on given approximately 5 s before ground
421 contact). In addition, significant correlations were observed between the peak knee
422 valgus moment measured during anticipated landings and pre-motor times (time
423 between a light stimulus and muscle activation in response) measured during a
424 choice reaction task (subjects were required to move either left or right from a
425 standing position in response to a light stimulus) for both medial gastrocnemius and
426 medial hamstrings. For both muscles, increased pre-motor times were associated
427 with increased knee abduction moment during the push off phase of the landing. The
428 findings of this study further strengthen the link between anticipation and knee valgus
429 moments and highlight a potentially important link between the function of the medial
430 muscles of the lower limb, in particular the medial hamstrings, during a reaction task
431 and valgus moment at the knee during landing.

432

433 Since initial research suggests that decision making influences landing
434 biomechanics, Brown et al. (2009) investigated the effects of altering the time prior to
435 landing of an unanticipated stimulus. Thirteen male and thirteen female recreational
436 athletes completed a task involving a 2 m forward jump which subjects were then

437 required to land from in single limb stance and immediately perform a vigorous cut to
438 the opposite side to the leg which they had landed on. The landing leg were given to
439 the subjects in an anticipated condition (5 s prior to the task) and during three
440 unanticipated conditions (approximately 600 ms, 500 ms and 400 ms prior to
441 landing), provided by a light stimulus in a randomised order. For task effects, the
442 results showed that at initial ground contact, subjects displayed significantly greater
443 hip abduction and less hip flexion in unanticipated conditions compared to the
444 anticipated conditions but there was no significant difference between the three
445 unanticipated conditions. Also, peak hip and knee external rotation moments during
446 the first 50% of the stance phase were significantly greater for two of the
447 unanticipated conditions (500 ms and 400 ms) compared to the unanticipated
448 condition. These results suggest that whilst the unanticipated nature of tasks affects
449 landing biomechanics, the timing of the unanticipated stimulus did not show any
450 effect on the biomechanics of landing within the time frames examined in this study.
451 Further investigation is needed into shorted pre-landing stimulus times to further
452 verify these findings.

453

454 These studies provide clear indication that decision making does influence the
455 biomechanics of landing/cutting, therefore future research should investigate tasks
456 involving an element of decision making to reflect game situations. Further
457 investigation is required to confirm any differences between males and females in
458 responses to decision making during landing/cutting since many of the findings from
459 the studies involve complex interactions between multiple independent variables
460 such as decision making, gender and type of task. At times, this makes interpretation

461 of the results difficult but highlights the multifactoral nature of biomechanical risk
462 factors associated with ACL injury.

463

464 **Conclusion**

465 There is general consensus that the biomechanical risk factors associated with the
466 gender difference in ACL injury incidence include less knee flexion at ground contact,
467 greater knee valgus motion, greater knee extension moment and greater knee valgus
468 moment in females than males during landing and cutting manoeuvres. Increasing
469 hamstring muscle force through altering strength, muscle activity, muscle length and
470 contraction velocity is likely to reduce these biomechanical risk factors. Recent
471 research has focussed on the influence of trunk motion and loading along with the
472 relationships between strength, muscle activity and landing/cutting biomechanics.
473 This research has shown that increased trunk flexion and greater hamstring strength
474 are associated with reduced ACL injury risk. Decision making has also been shown
475 to influence landing biomechanics and should be considered when designing tasks to
476 assess landing/cutting biomechanics. Coaches should therefore concentrate on
477 strength training of the hamstrings and encouraging athletes to actively flex the trunk
478 through incorporating training activities which involve decision making during landing
479 and cutting movements in an attempt to reduce ACL injury risk.

480

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705

706

707 **Figure Captions**

708 Figure 1. The forces acting on the proximal end of the tibia due to the quadriceps and
709 hamstrings and their moment arms in the sagittal plane. F_Q = force exerted by the
710 quadriceps, F_H = force exerted by the hamstrings, d_Q = moment arm of the
711 quadriceps (patella tendon), d_H = moment arm of the hamstrings, ACL = force
712 exerted by the ACL and PCL = force exerted by the PCL.

713

714 Figure 2. Anterior aspect of the proximal end of the left tibia and the forces acting on
715 the proximal end of the tibia due to the semimembranosus, semitendinosus, gracilis
716 and biceps femoris and their moment arms in the frontal plane. F_{SM} = force exerted
717 by the semimembranosus, F_{ST} = force exerted by the semitendinosus, F_{GR} = force
718 exerted by the gracilis, F_{BF} = force exerted by the biceps femoris, d_{SM} = moment arm
719 of the semimembranosus, d_{ST} = moment arm of the semitendinosus, d_{GR} = moment
720 arm of the gracilis, d_{BF} = moment arm of the biceps femoris, ACL = force exerted by
721 the ACL and PCL = force exerted by the PCL.

722

723 **Tables**

724 Table 1. Summary of studies examining the effects of trunk position and load on
 725 lower extremity biomechanics.

Study	Task	Independent variables	Key findings
Chaudhari et al. (2005)	90° cutting	Arm position (no constraint, holding ball in each arm, holding lacrosse stick)	Constraining plant side arm movement increased knee valgus moment
Jansen et al. (2012)	Two footed volleyball block jump landing	Load (9.89 kg weighted vest)	Hip flexion increased at initial contact when unloaded compared to loaded
Kulas et al. (2010)	45 cm two footed drop landing	Load (10% BW weighted vest) and trunk adaptation to load (extensors or flexors)	Added load increased KASF in trunk extensors and increased quadriceps and gastrocnemius forces in both groups. Hamstring force greater in trunk flexor group than extensor group when loaded
Kulas et al. (2008)	45 cm two footed drop landing	Load (10% BW weighted vest) and trunk adaptation to load (extensors or flexors)	Added trunk load and trunk position interactively affect hip biomechanics. Added trunk load increase the biomechanical demand on the knee and ankle regardless of trunk position
Blackburn et al. (2009)	60 cm two footed drop landing	Trunk position (preferred, active flexion)	Active trunk flexion reduced vGRF and pGRF and quadriceps muscle activity
Kulas et al. (2012)	Single leg squat	Trunk position (minimise forward lean, increased forward lean)	Peak ACL forces reduced when moderately increasing forward lean
Shimokochi et al. (2013)	Single leg drop (30 cm for females and 45 cm for males)	Trunk position (self-selected, forward lean, upright)	When compared to forward leaning landing, upright landing showed greater peak vGRF and peak knee extension moment, but less plantar flexion, hip extension moment and muscle activity of the MG, LG and LQ
Dempsey et al. (2012)	Single leg landing following a ball catch	Movement of ball (ball moved towards or away from support leg both early and late)	Movement of ball towards support leg resulted in increased knee valgus moment when compared to ball moving away. Significant positive correlation between trunk lateral flexion towards landing leg and knee valgus moment
Nagano et al. (2011)	180° cutting	Gender	Trunk forward and lateral inclination significantly greater in males than females. Strong positive correlation between trunk forward inclination and knee flexion
Frank et al. (2013)	60° cutting	Trunk motion	Greater knee varus moment associated with reduced trunk rotation away from stance limb (towards direction of travel).

726 BW = body weight, KASF = knee anterior shear force, vGRF = vertical ground reaction force, pGRF =
 727 posterior ground reaction force, MG = medial gastrocnemius, LG = lateral gastrocnemius, LQ = lateral
 728 quadriceps.