

1 Title: Differences between the sexes in knee kinetics during landing
2 from volleyball block jumps.

3 Running head: Knee kinetics during landing
4

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21

22 **Abstract.**

23 The purpose of the study was to investigate gender differences in frontal and sagittal plane
24 kinetics (normalised ground reaction force and normalised knee moment) in university
25 volleyball players when performing opposed block jump landings. Females displayed a
26 significantly lesser normalised knee extension moment at the start of muscle latency than
27 males. The greater normalised knee extension moment at the start of muscle latency in
28 females suggests that through practise, the female subjects may have developed a landing
29 strategy that minimises the moment acting about the knee in the sagittal plane to reduce the
30 likely strain on the passive support structures. The time histories of the normalised knee
31 moment in the frontal plane were different between males and females. The maximum
32 normalised knee valgus moment was significantly greater in females than males. The
33 significantly different maximum normalised knee valgus moment between males and females
34 indicates greater likelihood of overloading the muscles of the knee in females during landing
35 which in turn is likely to increase the strain on the passive support structures. The increased
36 likely strain on the passive support structures of the knee in females could contribute to the
37 reported greater incidence of non-contact ACL injury in females compared to males.

38

39 **Introduction.**

40 Research suggests that between 70% and 90% of anterior cruciate ligament (ACL) injuries
41 occur in non-contact situations (Griffin, et al., 2000; McNair, Marshall, & Matheston, 1993;
42 Mykelbust, Maehlum, Engbretsen, Strand, & Solheim, 1997), i.e., no direct contact with the
43 knee at the time of injury. ACL injury appear to occur most frequently during movements
44 such as landing (Hopper & Elliot, 1993), deceleration (Miller, Cooper, & Warner, 1995) or
45 rapid change of direction (Olsen, Mykelbust, Engebretsen, & Bahr, 2004). The incidence of
46 ACL injury is therefore high in sports involving a high frequency of landing, decelerating and

47 rapid changes of direction (e.g. basketball, netball, handball and volleyball) (Arendt & Dick,
48 1995; Griffin et al., 2000). The incidence of non-contact ACL injury has been reported to be 6
49 to 8 times greater in females than in males competing in the same sports (Arendt & Dick,
50 1995; Chandy & Grana, 1985; Ferretti, Papandrea, Conteduca, & Mariani, 1992; Gray et al.,
51 1985; Gwinn, Wilckens, & McDevitt, 2000; Lidenfeld, Schmitt, & Hendy, 1994; Malone,
52 Hardaker, & Garrett, 1993). A number of potential risk factors have been proposed to account
53 for this gender difference in the incidence of non-contact ACL injury. These include
54 intercondylar notch width (Ireland, Balantyne, Little, & McClay, 2001), Q angle (Shambaugh,
55 Klein, & Herbert, 1991), patella tendon tibia shaft angle (Nunley, Wright, Renner, Yu, &
56 Garrett, 2003), ACL cross sectional area (Charlton, St John, Ciccotti, Harrison, & Scheitzer,
57 2002), joint laxity (Uhorchak et al., 2003), hormonal influences (Wojtys, Huston, Boynton,
58 Spindler, & Lindenfeld, 2002), muscle strength (Salci, Kentel, Heycan, Akin, & Korkusus,
59 2004), muscle stiffness (Wojtys, Huston, Shock, Boylan, & Ashton-Miller, 2003), muscle
60 activity patterns (Zeller, McCrory, Ben Kibler, & Uhl, 2003) and biomechanics of landing
61 (Chappell, Yu, Kirkendall, & Garrett, 2002; Salci et al, 2004; Yu, Lin, & Garrett, 2006;
62 Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005; Decker, Torry, Wyland, Sterett, &
63 Steadman, 2003). However, the only evidence (uni-variate correlation based on small
64 samples) in support of gender differences with regard to some risk factors, such as Q angle,
65 joint laxity, intercondylar notch width, ACL cross sectional area and hormones, is fairly weak.
66 The evidence in support of gender differences with regard to some of the factors affecting the
67 dynamic stability of the knee, in particular gender differences in landing biomechanics
68 (Chappell et al., 2002; Salci et al., 2004; Yu et al., 2006; Kernozek et al., 2005) is much
69 stronger.

70

71 During landing the ankle, knee and hip joints will move from a position of relative extension
72 to flexion as the downward linear momentum of the body is reduced to zero. These joint
73 movements are determined by the net moments acting about the joints. It takes a certain
74 amount of time (latency period of the muscles) for the muscles to fully respond to the ground
75 reaction force (GRF). Muscle latency varies between 30 ms and 75 ms (Nigg et al., 1984;
76 Watt & Jones, 1971). Whilst muscle activity prior to landing may play a role, for changes in
77 external load that occur in less than the latency period of muscles the body is forced to
78 respond predominantly passively to the external load. During this period of passive loading,
79 the body is vulnerable to injury from high forces within the tissues of the joint that occur as a
80 result of high GRF and/or high external moments about the joints arising from the GRF. After
81 the passive loading phase, the magnitude and direction of the GRF is primarily controlled by
82 conscious muscular activity, referred to as the active loading phase. During active loading, the
83 muscles primarily determine the magnitude and direction of the GRF in order to try to prevent
84 substantial GRF moments about the lower limb joints and therefore reduce the risk of injury.
85 It is, perhaps, not surprising that ACL injury appears to occur most often just after initial
86 ground contact (Boden, Dean, Feagin, & Garrett, 2000; Olsen et al., 2004), i.e. during passive
87 loading.

88

89 Studies examining knee moments and GRF during landing indicate that females tend to
90 exhibit greater normalised peak knee extension moment (Chappell et al., 2002; Salci et al.,
91 2004; Yu et al., 2006) and greater normalised peak GRF (Kernozek et al., 2005; Salci et al.,
92 2004; Yu et al., 2006) than males. There is very little empirical data available on knee
93 moment in the frontal plane during landing. Chappell et al. (2002) found females to display
94 greater normalised knee valgus moment than males, whereas Kernozek et al. (2005) found
95 females to display lower normalised knee varus moment than males in landing manoeuvres.

96 However, lack of appropriate standardisation in task demands may have invalidated
97 meaningful comparison between females and males. For example, dropping down from a
98 raised platform set at the same height for both males and females (Decker et al., 2003; Salci et
99 al., 2004; Kernozek et al., 2005) may result in significantly different task demands. To our
100 knowledge, no study has examined gender differences in knee kinetics when performing sport
101 specific tasks with the inclusion of opposition. Table 1 shows the results of a number of
102 studies that have reported group mean data for ground reaction force and moment about the
103 knee in landing manoeuvres.

104 _____
105 Table 1 about here.
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107

108 The greater the external moment (moment due to the GRF during landing) about the knee
109 joint axis the greater the resultant moment about the knee joint is likely to be and therefore,
110 the greater the risk of overloading the muscles about the knee joint. Since knee joint stability
111 (i.e., prevention of abnormal joint movement) is maintained by dynamic (contractile) and
112 passive (non-contractile) support structures, the greater the load on the muscles, i.e. dynamic
113 support structures, the greater the extent to which stability of the knee joint is likely to be
114 maintained by the passive support structures, in particular the ACL, posterior cruciate
115 ligament (PCL), lateral and medial ligaments. If the load on the passive support structures
116 exceeds their strength, injury is likely to occur. Consequently, the reported increased
117 incidence of ACL injury in females during landing movements may be due, in part, to greater
118 peak normalised knee extension moment and greater normalised ground reaction force.
119 Further investigation is needed concerning the influence of moments in the frontal plane
120 during landing/cutting on the gender difference in the incidence of non-contact ACL injury.

121

122 The aim of the study was to investigate the effects of gender on knee kinetics in university
123 volleyball players performing block jump landings in opposed conditions. It was hypothesised
124 that males and females would display different knee joint moments and GRF in the sagittal
125 and frontal planes during landing from volleyball block jumps which may be indicative of a
126 greater likelihood of ACL injury in females compared to males.

127

128 **Method.**

129 **Subjects.**

130 Six female (Mean age 21.7 ± 1.5 years, mass 58.1 ± 6.2 kg and height 165.2 ± 7.1 cm) and six
131 male (Mean age 22.2 ± 2.6 years, mass 72.1 ± 4.5 kg and height 177.1 ± 9.4 cm) university
132 volleyball players participated in the study. All subjects were right leg dominant and had no
133 previous history of hip, knee or ankle injury. Ethical approval was granted for the study by the
134 University Ethics Committee and written consent forms were signed by all subjects prior to
135 data collection.

136

137 **Measurement system.**

138 An AMTI force platform sampling at 600 Hz was used to measure the GRF and the location
139 of the centre of pressure acting on the right leg during landing. A time synchronised 12
140 camera Vicon 512 system (Vicon, Oxford, England) sampling at 120 Hz was used to
141 determine 3D coordinates of 8 retro-reflective markers (25 mm diameter). Markers were
142 placed directly on the skin of each subject's right (dominant) leg in accordance with the Vicon
143 system's lower body plug-in gait marker set. All subjects wore tight fitting clothing in order
144 to minimise marker occlusion. The marker locations were: anterior superior iliac spine,
145 posterior superior iliac spine, lower lateral surface of the thigh along the line between the hip

146 and knee joints, lateral epicondyle of the femur, lower lateral surface of the tibia along the
147 line between knee and ankle joints, lateral malleolus of the ankle, superior proximal end of the
148 second metatarsal, posterior aspect of the Achilles tendon at the same height as the second
149 metatarsal marker. From the location of the markers placed on the body, combined with
150 required anthropometric measurements of each subject entered into the system, the Vicon
151 system calculated the 3D coordinates of hip, knee and ankle joint centres. The subject
152 anthropometric measurements required were height, weight, leg length, knee width and ankle
153 width. The Vicon system uses the Newington-Gage model to define the positions of the hip
154 joint centres within the pelvis segment (in which pelvis size and leg length are used as scaling
155 factors) in conjunction with the markers placed on the pelvis and leg length measurement to
156 determine the 3D position of hip joint centre (Davis, Ounpuu, Tyburski, & Gage, 1991). The
157 knee joint centre is determined from hip joint centre, knee marker, thigh marker and knee
158 width measurement. The ankle joint centre is determined from the knee joint centre, ankle
159 marker, tibia marker and ankle width measurement.

160

161 Angular definitions.

162 In the Plug-in gait system, the measurement of knee flexion/extension is based on the thigh
163 axis (line connecting the hip joint and knee joint centres) and the shank axis (line connecting
164 the knee and ankle joint centres) projected onto the plane of knee flexion/extension (as
165 determined by the plug-in gait marker system). The flexion/extension angle is the angle
166 between the distal extension of the thigh axis and the shank axis. A positive angle corresponds
167 to knee flexion relative to the fully extended position. The measurement of knee valgus/varus
168 is based on the thigh axis and the shank axis projected onto the plane of knee valgus/varus
169 (defined as perpendicular to the knee flexion/extension axis). The valgus/varus angle is the

170 angle between the distal extension of the thigh axis and the shank axis. A positive angle
171 indicates varus and a negative angle indicates valgus.

172

173 Moment definitions.

174 The inverse dynamics approach to calculating the moments acting about a joint is the most
175 accurate method as it takes into consideration all of the possible component moments.

176 However, when the segment mass is small and the linear and angular accelerations of the
177 segment centre of gravity are small relative to external moment, the more closely the external

178 moment will approximate the moment acting about a joint (Winter, 1990). When this is the
179 case, the quasi-static model for calculating the joint moment is justifiable (Alexander &

180 Vernon, 1975; Harrison, Lees, McCullagh, & Rowe, 1986; Hewett, Stroupe, Nance, & Noyes,
181 1996; Smith, 1975). Alexander and Vernon (1975) found that in two 68 kg male subjects

182 landing from a 0.81 m vertical drop the effect of the segment mass and the linear and angular
183 accelerations of the segment centre of gravity were small in relation to external moment

184 (moment due to the GRF) when calculating the moment about the knee joint centre. For
185 example, during landing the peak moment about the knee was estimated at 120 N.m using the

186 quasi-static model which was decreased by 9 N.m when segment mass and the linear and
187 angular accelerations of the segment centre of gravity were included. Therefore, the quasi-

188 static model was used to estimate the moment about the knee joint centre of the right leg in
189 the sagittal and frontal planes during landing.

190

191 The GRF moment was calculated using the cross product $\mathbf{r} \times \mathbf{F}$ where \mathbf{r} = position vector of
192 the point of application of \mathbf{F} (centre of pressure) with respect to the knee joint centre and \mathbf{F} =

193 ground reaction force vector. In the sagittal plane, a GRF moment that tends to extend the

194 knee, using the quasi-static approach, is considered to be equal and opposite to a
195 corresponding knee flexion moment. Similarly, a GRF moment that tends to flex the knee
196 results in a corresponding knee extension moment. In the frontal plane, a GRF moment that
197 tends to adduct the knee (move into a varus position), using the quasi-static approach, is
198 considered to be equal and opposite to a corresponding knee valgus moment. Similarly, a
199 GRF moment that tends to abduct the knee (move into a valgus position) results in a
200 corresponding knee varus moment.

201

202 Landing Task.

203 Prior to data collection all subjects performed a 10-min warm up consisting of lower limb
204 stretching and running/jogging on a treadmill at self determined speeds. When this was
205 completed, subjects practised the jumping and landing task until comfortable with the
206 procedure. Whilst previous studies have examined gender differences in knee kinetics during
207 landing from vertical drops from standardised heights without the inclusion of opposition
208 (Decker et al., 2003; Salci et al., 2004; Kernozek et al., 2005), in the present study, the
209 jumping and landing task was made as realistic as possible by having subjects attempt to
210 block an actual spike performed by an experienced volleyball player in an attempt to improve
211 the ecological validity of the data obtained. To do this, a rope fixed horizontally 5 cm in front
212 of the force platform to act as a volleyball net at a height of 2.43 m for male subjects and 2.24
213 m for female subjects (height of a standard volleyball net). Also, a volleyball was suspended
214 from the ceiling and positioned with the bottom of the ball 5 cm above the net (2.48 m for
215 males and 2.29 m for females) and with the centre of the ball 10 cm in front of the line of the
216 net (the other side of the net to where the subject (blocker) was standing). At the start of each
217 trial, the subject stood with their right foot on the force platform. The subject then timed

218 his/her blocking action in order to try to block the ball as it was spiked. The ball was spiked
219 from the same suspended position in order to eliminate variation in the position and velocity
220 of the ball. On landing, only the right foot landed on the force platform and trials where the
221 right foot did not land entirely on the force platform were discarded. Data was recorded for
222 three successful trials for each subject.

223

224 Data analysis.

225 The 3D coordinate data were filtered using a Woltring Filter. To alter the filter settings a
226 mean squared error (MSE) tolerance value was entered into the Vicon system. The MSE
227 method allows the noise level to be input and a spline function is fitted to the data points in
228 accordance with the specified level of tolerance. Consistent application of this processing
229 method ensured the same level of smoothing for all marker trajectories. Based on a primary
230 consideration of minimising high frequency artefacts whilst maintaining the detail of the
231 signal at all lower frequencies, it was determined that it would be most appropriate to use a
232 MSE value of 50 as a suitable setting for filtering the data. This was determined by analysing
233 the effects of a number of different filter settings for sample data of a number of different
234 jumps and from a number of different subjects. In determining a suitable MSE value, the data
235 were analysed using a Welch periodogram to provide power spectral density (PSD) plots that
236 quantify the magnitude of power in a narrow frequency band (in this case the bandwidth was
237 1/120 Hz). From the PSD plots, the estimated frequency of the start of signal attenuation, 50%
238 of signal attenuation and almost complete signal attenuation could be determined for the MSE
239 value of 50. The filter setting determined to be most appropriate for these data (i.e. MSE = 50)
240 corresponded to a low-pass filter of cut-off frequency 10 Hz and stop-band frequency of 30
241 Hz.

242

243 The GRF, knee angle and the knee moment in the sagittal (flexion/extension) and frontal
244 (valgus/varus) planes were determined between initial ground contact (IC) and, depending on
245 which occurred later in the trial, either maximum knee flexion or maximum knee valgus/varus
246 angle (MAX) in each trial. All data were then normalised with respect to average trial time.
247 Figures show variables plotted against normalised time and against absolute mean trial time
248 between IC and MAX. Absolute mean contact time was $0.190 \text{ s} \pm 0.040$ for males and 0.194 s
249 ± 0.057 for females. As there was no significant difference between contact time for males
250 and females, mean contact time of 0.192 s was used. GRF was normalised to body weight (in
251 Newtons) and knee moments were normalised to body weight (in Newtons) and height (in
252 metres). Mean data were based on 18 trials for males (6 subjects \times 3 trials \times 1 leg) and 18
253 trials for females (6 subjects \times 3 trials \times 1 leg). Independent-samples t-tests were carried out
254 on the GRF, knee angle and moment about the knee data in the sagittal and frontal planes at
255 the start of the muscle latency period (ML) (0.03 s), the start of the active loading period (AL)
256 (0.075 s), at MAX and minimum and maximum values to examine gender differences. Due to
257 multiple t-tests being carried out on samples taken from the same population, to reduce the
258 chance of type I error, a Bonferroni adjustment was made to the alpha level.

259

260 **Results.**

261 Group mean curves for normalised GRF, knee angle and normalised knee moment (+ve =
262 flexion moment, -ve = extension moment) throughout the landing period in the sagittal plane
263 for males and females are shown in Figure 1. With regard to normalised GRF (Figure 1a), the
264 overall shapes of the curves were similar for males and females, i.e. increase during the
265 passive loading phase (PP) (IC to 0.075 s) followed by decrease during the active loading
266 phase (AP) (0.075 s to MAX). For most of the landing period, the normalised GRF was
267 greater for males than females. The main difference between males and females occurred

268 during PP where females exhibited a smaller initial peak which also occurred earlier in the
269 landing phase than in males. There was no significant difference between males and females'
270 normalised GRF at ML, AL, MAX or maximum normalised GRF (Table 2).

271 _____

272 Figure 1 about here.

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276 Table 2 about here.

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278

279 Females and males exhibited a progressive increase in knee flexion during the landing phase
280 (Figure 1b). Females exhibited significantly greater MAX knee flexion (Table 2). There was
281 no significant difference in knee flexion angle between males and females at ML or AL.

282

283 During PP, females exhibited a smaller peak in normalised knee extension moment than
284 males, which occurred earlier during the landing phase in females than in males (Figure 1c).

285 During AP, the normalised knee extension moment was very similar in males and females.

286 Females displayed a significantly smaller normalised knee extension moment at ML than

287 males. There was no significant difference in the normalised knee extension moment between

288 males and females at AL, at MAX or the maximum and minimum values (Table 2). The

289 magnitude of the standard deviation of the normalised knee moment data at 1% normalised

290 time intervals was very similar between IC and MAX in males and females (Figure 1c). Mean

291 stick figures of the angle of the knee and the normalised GRF vector in the sagittal plane for

292 males and females at ML, AL and MAX are shown in Figure 2.

293

294 _____
295 Figure 2 about here.
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299 Group mean curves for normalised GRF, knee angle and normalised knee moment (+ve =
300 valgus moment, -ve = varus moment) in the frontal plane throughout the landing period are
301 shown for males and females in Figure 3. Since Fy (mediolateral force) and Fx
302 (anterioposterior force) were small relative to Fz (vertical force) during landing, the resultant
303 normalised GRF in the frontal plane (Figure 3a) was very similar to the resultant normalised
304 GRF in the sagittal plane. Therefore as with the resultant normalised GRF in the sagittal
305 plane, the resultant normalised GRF in the frontal plane was similar in shape in males and
306 females, was greater for males than females during most of the landing phase and the main
307 difference between males and females occurred during PP where females exhibit a smaller
308 initial peak which occurred earlier in the landing phase than in males. There was no
309 significant difference between males and females' normalised GRF at ML, AL, MAX or
310 maximum GRF (Table 3).

311 _____
312 Figure 3 about here.
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315 _____
316 Table 3 about here.
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319 In the frontal plane, females tended to contact the ground with the angle of the knee in a
320 valgus position (-ve values) which progressively increased between IC and MAX. In contrast,
321 males tended to contact the ground in a valgus position and maintained a valgus position
322 throughout the landing phase (Figure 3b). The amount of valgus at ML and AL were not

323 significantly different between males and females. However, the maximum knee valgus angle
324 was significantly greater in females compared to males (Table 3).

325
326 The normalised knee moment (Figure 3c) remained in valgus throughout the landing phase for
327 females, with an increase in normalised knee valgus moment during PP and a decrease during
328 AP. However, for males, the normalised knee moment in the frontal plane was varus at IC,
329 which increased then decreased until it changed to a valgus moment close to ML. The
330 normalised knee moment in the frontal plane then changed back to varus at approximately
331 30% normalised time and remained in varus until MAX. At AL, the normalised knee varus
332 moment in males was significantly different from the normalised knee valgus moment in
333 females. The maximum normalised knee valgus moment was significantly greater in females
334 than males. There was no significant difference in the normalised knee moment in the frontal
335 plane at ML, MAX or maximum normalised knee varus moment between males and females
336 (Table 3). The magnitude of the standard deviation of the normalised knee moment data at 1%
337 normalised time intervals was very similar between IC and MAX. This is illustrated in Figure
338 3c. Mean stick figures of the angle of the knee and the normalised GRF vector in the frontal
339 plane at ML, AL and MAX for males and females are shown in Figure 4.

340 _____
341 Figure 4 about here.
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343

344 **Discussion.**

345 Maximum normalised GRF in both the frontal and sagittal planes were not significantly
346 different between females and males. This is different to a number of other studies which
347 found females to exert greater normalised GRF than males when landing (Kernozek et al.,
348 2005; Salci et al., 2004; Yu et al., 2006). This may be due to other studies having males and

349 females dropping down from the same fixed height, whereas this study had subjects jumping
350 up to block a ball at a height of 2.43 m for males and 2.24 m for females. It is unlikely
351 females jump as high as males when playing those sports where non-contact ACL injury is
352 particularly common, particularly volleyball as the net is 0.19 m higher for males than
353 females. Also, in the present study, the GRF acting on the right leg was measured and not the
354 combined GRF acting on the right and left legs as in previous studies (Kernozek et al., 2005;
355 Salci et al., 2004; Yu et al., 2006).

356

357 The maximum normalised knee extension moment was not significantly different between
358 females and males, contrary to a number of other studies (Chappell et al., 2002; Salci et al.,
359 2004; Yu et al., 2006). This again may be due to differences in task demands and differences
360 in subject playing standard between previous studies and the present study. The normalised
361 knee extension moment at ML was significantly smaller in females than males. Also, the
362 normalised knee extension moment was smaller in females than males during the majority of
363 the landing phase. This suggests that through training, females may have developed a strategy
364 of landing which minimises the moment acting about the knee in the sagittal plane in an
365 attempt to reduce the likely strain on the dynamic and passive support structures of the knee.
366 For the male and female groups, the maximum normalised knee extension moment in this
367 study was very similar to that reported by Hewett et al., (1996). For example, values for the
368 maximum normalised knee extension moment reported by Hewett et al., (1996) were 0.104
369 BW.ht for trained females and 0.158 BW.ht for untrained males compared to 0.110 BW.ht for
370 trained females and 0.1325 BW.ht for trained males in the present study.

371

372 In males, the normalised knee moment in the frontal plane was small in comparison to
373 females (Figure 3) and changed between valgus and varus during landing. In females

374 however, the normalised knee valgus moment was greater than in males (Figure 3) and
375 remained in valgus throughout the entire landing phase. At AL, the normalised knee varus
376 moment in males was significantly different from the normalised knee valgus moment in
377 females and the maximum normalised knee valgus moment was significantly greater in
378 females than males. The greater maximum knee valgus moment in females indicates greater
379 likelihood of overloading the muscles of the knee, in particular the muscles attached to the
380 medial and lateral aspects of the tibia, such as the gracilis, semitendinosus, semimembranosus
381 and biceps femoris. The greater loading of the muscles in females is therefore likely to
382 indicate a greater possibility of strain on the passive support structures of the knee during
383 landing in maintaining joint stability. Furthermore, the structure of the knee joint only allows
384 one main degree of freedom, i.e. angular motion about a mediolateral axis (knee
385 flexion/extension). The normal ranges of motion in the other five degrees of freedom (3 linear
386 planes and 2 angular) are very small. Consequently, the quadriceps and hamstrings facilitate
387 knee flexion and extension, but tend to stabilise the knee with respect to the other 5 degrees of
388 freedom. Therefore, due to the structure of the knee, a moment acting about the knee in the
389 frontal plane is more likely to induce abnormal movement of the knee joint than similar
390 moment in the sagittal plane, which in turn is more likely to overload the stabilising structures
391 (passive and dynamic) of the knee.

392

393 Hewett et al., (1996) reported values of 0.021 BW.ht for maximum normalised knee valgus
394 moment for trained females. These values are similar to those reported in the present study of
395 0.0208 BW.ht for females. Hewett et al., (1996) reported values of -0.017 BW.ht for
396 maximum normalised knee varus moment for trained females. However, in this study,
397 throughout the landing phase used for analysis (between IC and MAX) the normalised knee
398 moment remained in valgus for females. In untrained males, Hewett et al., (1996) reported

399 values of 0.037 BW.ht for maximum normalised knee valgus moment and -0.049 BW.ht for
400 maximum normalised knee varus moment. These values appear slightly higher than those
401 measured in the present study for trained males, which are a maximum normalised knee
402 valgus moment of 0.0116 BW.ht and a maximum normalised knee varus moment of -0.0164
403 BW.ht. The differences in the data reported by Hewett et al., (1996) and the present study for
404 males are likely to be due to differences in the training status of the subjects, i.e. Hewett et al.,
405 (1996) examined untrained males whereas the present study examined trained males.

406

407 **Conclusion.**

408 The overall patterns of the normalised GRF were similar between males and females in both
409 the sagittal and frontal planes during landing. The normalised knee extension moment was
410 similar in pattern between males and females. Females displayed significantly smaller
411 normalised knee extension moment at ML than males. The patterns of the normalised knee
412 moment in the frontal plane were different between males and females. Females normalised
413 knee moment remained in valgus throughout landing (slight increase during PP followed by
414 decrease during AP), whereas for males, the normalised knee moment changed between
415 valgus and varus during landing. The normalised knee varus moment exhibited by males was
416 significantly different from the normalised knee valgus moment exhibited by females at AL
417 and the maximum normalised knee valgus moment was significantly greater in females than
418 males. These results indicate greater likelihood of overloading the muscles of the knee in the
419 frontal plane during landing in females which in turn is likely to increase the strain on the on
420 the passive support structures of the knee in maintaining joint stability. This could contribute
421 to the reported greater incidence of non-contact ACL injury in females compared to males.
422 Training programmes for females should incorporate exercises and practices to alter the

423 moments exhibited by females in the frontal plane to reduce the likely strain on the passive
424 support structures of the knee.

425

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521

522 **Tables.**

523 Table 1. Group mean data for ground reaction force and moments about the knee in landing
 524 manoeuvres in males and females.

Study.	Task	Sagittal plane knee moment.	Frontal plane knee moment.	Ground reaction forces.
Salci et al., (2004)	40 cm and 60 cm vertical drop landing.	F displayed significantly greater peak knee extension moment than M at 40 cm drop landing (M; 0.1±3.2 Nm/kgBM; F; 3.0±2.2 Nm/kgBM).		F exhibited significantly greater normalised peak vertical ground reaction force than M in both 40 and 60 cm drop landing (mean- M: 3.8±0.7 BW; F; 5.4±0.9 BW) .
Decker et al., (2003)	60 cm vertical drop landing.	No significant difference between M and F peak knee extension moment (M; 17.69±4.57 %BW.ht; F; 15.31±3.3 %BW.ht).		No significant difference between M and F peak normalised vertical ground reaction force (M; 3.67±0.92 BW; F; 3.39±0.89 BW).
Chappell et al., (2002)	Forward, backward and vertical stop-jump landing.	F exhibited a significantly greater knee extension moment than M in all tasks (mean estimated from graphs (+ flex, – ext) M; +0.05±0.2 BW.ht; F; -0.03±0.05 BW.ht).	F displayed a significantly greater knee valgus moment than M in all tasks (mean estimated from graphs (+ var, – val) M; +0.02±0.05 BW.ht; F; -0.02±0.06 BW.ht).	
Kernozek et al., (2005)	60 cm vertical drop landing.	No significant difference between M and F peak knee extension moment (M; 1.75±0.37 Nm/kgBM; F; 1.70±0.27 Nm/kgBM).	F displayed significantly lower peak knee varus moment than M (M; 1.61±0.72 Nm/kgBM; F; 0.93±0.69 Nm/kgBM).	F exhibited significantly greater normalised peak vertical ground reaction force than M (M; 3.51±0.63 BW; F; 4.71±0.71 BW).
Yu et al., (2006)	Stop-jump landing.	F displayed significantly greater peak knee extension moment than M (M; 0.15±0.04 BW.ht; F; 0.18±0.05 BW.ht).		F exerted significantly greater normalised peak vertical ground reaction force than M (M; 2.16±0.60 BW; F; 2.67±0.95 BW).

525 F = females, M = males.

526

527

528 Table 2. Group mean results for sagittal plane normalised GRF, knee angle and normalised
 529 knee moment (+ve = flexion moment, -ve = extension moment) at ML, AL, MAX maximum
 530 and minimum (Mean \pm standard deviation).

Sagittal plane		ML (0.03 s)	AL (0.075 s)	MAX	Maximum	Minimum
Normalised GRF (BW)	Male	1.052 \pm 0.170	1.772 \pm 0.485	0.972 \pm 0.415	1.861 \pm 0.595	NA
	Female	1.160 \pm 0.287	1.625 \pm 0.415	0.894 \pm 0.378	1.631 \pm 0.427	NA
Flexion / extension ($^{\circ}$)	Male	28.83 \pm 5.30	43.60 \pm 7.78	62.97 \pm 11.24 ¹	NA	NA
	Female	24.88 \pm 4.97	46.66 \pm 9.05	68.22 \pm 9.49 ¹	NA	NA
Normalised moment (BW.ht)	Male	-0.0433 \pm 0.0353 ²	-0.1110 \pm 0.0541	-0.0908 \pm 0.0303	-0.1325 \pm 0.0681	-0.0097 \pm 0.0166
	Female	-0.0065 \pm 0.0325 ²	-0.0876 \pm 0.038	-0.0923 \pm 0.048	-0.1100 \pm 0.0309	-0.0055 \pm 0.0227

531 ¹⁺² Significant difference between males and females

532 Table 3. Group mean results for frontal plane normalised GRF, knee angle and normalised
 533 knee moment (+ve = valgus moment, -ve = varus moment) at ML, AL, MAX maximum and
 534 minimum (Mean \pm standard deviation).

Frontal plane		ML (0.03 s)	AL (0.075 s)	MAX	Maximum	Minimum
Normalised GRF (BW)	Male	1.054 \pm 0.173	1.778 \pm 0.486	0.977 \pm 0.418	1.864 \pm 0.595	NA
	Female	1.150 \pm 0.302	1.601 \pm 0.412	0.890 \pm 0.378	1.604 \pm 0.421	NA
Valgus / varus ($^{\circ}$)	Male	-0.10 \pm 7.04	-1.09 \pm 7.84	-1.38 \pm 9.20 ¹	NA	NA
	Female	-3.00 \pm 3.23	-4.54 \pm 4.41	-6.79 \pm 4.50 ¹	NA	NA
Normalised moment (BW.ht)	Male	0.0058 \pm 0.0173	-0.0085 \pm 0.0212 ²	-0.0025 \pm 0.0106	0.0116 \pm 0.0170 ³	-0.0164 \pm 0.0176
	Female	0.0192 \pm 0.0199	0.0187 \pm 0.0200 ²	0.0047 \pm 0.0127	0.0208 \pm 0.0199 ³	0.0047 \pm 0.0127

535 ¹⁻³ Significant difference between males and females.

536

537 **Figure captions.**

538 Figure 1. Sagittal plane normalised GRF, knee angle and normalised knee moment between
539 IC and MAX for males and females.

540 Figure 2. Mean stick figures of males (a) and females (b) knee angle and normalised GRF
541 vector in the sagittal plane at the start of muscle latency, start of active loading and maximum
542 angle of the knee.

543 Figure 3. Frontal plane normalised GRF, knee angle and normalised knee moment between IC
544 and MAX for males and females.

545 Figure 4. Mean stick figures of males (a) and females (b) knee angle and GRF vector in the
546 frontal plane at the start of muscle latency, start of active loading and maximum angle of the
547 knee.

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